1960

Excitation of carriers from imperfections in diamond

Jarl Avard Elmgren

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EXCITATION OF CARRIERS FROM IMPERFECTIONS IN DIAMOND

by

Jarl Avard Elmgren

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# TABLE OF CONTENTS

## I. INTRODUCTION

A. Review of Some Diamond Characteristics  
   1. Structure and bulk properties 1  
   2. Optical properties 3  
   3. Charge transport properties 13  

B. The Diamond as a Nuclear Radiation Detector 20  
   1. Theory of pulse height 20  
   2. Properties of the diamond counter 27  

C. Essence of This Investigation 31  
   1. Purpose 31  
   2. Previous work in this field 32  
   3. General method 34  
   4. Advantages of the method 36  

## II. INSTRUMENTATION

A. Introduction 38  
   1. Apparatus characteristics for pulse detection 38  
   2. Preview of the equipment 42  

B. The Individual Components 43  
   1. The basic counting system 43  
   2. The count recording equipment 48  
   3. The source of controlled illumination 50  
   4. Auxiliary equipment 56  

C. The Assembled Apparatus 56  

## III. PROCEDURE

A. Sample Preparation and Preliminary Testing 59  
B. Creation of an Internal Field 61  
C. Decay of the Internal Field 63  
   1. Transition from applied field to internal field conditions 64  
   2. Observation of the dark decay 65  
   3. Observation of the photon-induced decay 67
D. Restoration to the Initial State

IV. EXPERIMENTAL DATA
A. Description of the Diamonds
B. Applied Field Counting Rate Data
   1. Diamond One
   2. Diamond Four
C. Internal Field Counting Rate Data
   1. Diamond One
   2. Diamond Four

V. DATA ANALYSIS AND RESULTS
A. Conversion of Counting Rate to Internal Field
   1. Mechanics of the conversion
   2. Examples of the conversion
B. Specification of Decay Constants
C. Effect of Light Intensity
   1. Idealized situation
   2. Actual situation
   3. Intensity effect - Diamond One
   4. Intensity effect - Diamond Four
D. Effect of Photon Energy on Internal Field Decay
E. An Alternate Analysis
   1. Application and results - Apparatus II
   2. Application and results - Apparatus I

VI. INTERPRETATION
A. The First Interpretation: Detrapping Model
   1. Qualitative interpretation
   2. Band model and decay mechanisms
   3. Quantitative interpretation
   4. Discussion
B. The Second Interpretation: Photoconductivity Model
   1. Qualitative interpretation
   2. Band model and decay mechanism
3. Quantitative interpretation 127
4. Discussion 132

VII. DISCUSSION 135

A. Critique of the Experiment 135
   1. Reproducibility 135
   2. Validity of the internal field conversion 138
   3. Discussion of errors 139

B. Some Puzzles 141
   1. Relaxation of an internal field by conduction 141
   2. Detrapping by red light 144

VIII. CONCLUSIONS AND RECOMMENDATIONS 146

A. Conclusions 146
B. Recommendations 147

IX. LITERATURE CITED 149

X. ACKNOWLEDGMENTS 152

XI. APPENDICES 153

A. Appendix A: Apparatus I 153
   1. Description of the components 153
   2. Component relationships 157

B. Appendix B: Synopsis of Experimental Data 157
C. Appendix C: Dependence of the Counting Rate on Electric Field 187
   1. The basic method 187
   2. Apparatus and procedure 188
   3. Presentation and analysis of the data 189
   4. Results 193
   5. Discussion 193

D. Appendix D: Determination of the Photon Flux Density from the Observed Photocell Current 198
   1. Photon flux density determination for the idealized situation 199
   2. Photon flux density determination for the actual situation 200
3. Photocell sensitivity calibration 203
4. Final results for the conversion to photon flux density 208
5. Error analysis 209

E. Appendix E: Intensity Effect Plots 213
F. Appendix F: Auxiliary Experiments 230

1. Dark polarization 230
2. Growth of the internal field during the applied field counting period 231
I. INTRODUCTION

Diamond has been treasured for centuries as a gem because of its brilliance - a result of its high refractive index and crystal structure. The extreme hardness of diamond is utilized in the manufacture of cutting and grinding tools by industry. However, these diamond properties which result in its commercial uses are only the most obvious of many unusual properties. Careful investigations of the unusual properties are just beginning to be reported. The investigation reported in this thesis was undertaken to increase the understanding of some of the electrical properties of diamond, and to relate these to some optical properties.

A. Review of Some Diamond Characteristics

A brief review of some important diamond characteristics which are related to the work reported in this thesis will be presented below. The review will serve not only as an introduction to this thesis, but as a synopsis of some more recent published material.

1. Structure and bulk properties

   a. Structure The space lattice of diamond is face-centered cubic with two atoms associated with each lattice point. It is often more pictorially described as two interpenetrating face-centered cubic lattices displaced along the major body diagonal of a unit cell by one-fourth of the length
of the diagonal. The tetrahedral bond arrangement is illustrated in many books (see, for instance, p. 37 of Kittel (1)). The covalent bonding of the carbon atoms in diamond is the basis of the extreme hardness and high binding energy.

Many optical and electrical properties of diamond are rather easily interpretable by the band theory as applied to diamond. The essentials of the general theory are presented by Kittel (1) among others. A result of the theory is that allowed electron energy levels for a solid are grouped into bands separated by regions of energy which are forbidden to the electrons of the normal atoms. In a perfect diamond at the absolute zero of temperature, the allowed energy states in the valence band are completely full of electrons, while the allowed states in the conduction band are entirely empty. This is the condition for no electrical conduction through the solid, so the fact that diamond is an electrical insulator is understandable. Discrete energy levels of impurity atoms or other imperfections often lie in the forbidden energy region. These imperfections have profound effects on some of the optical and electrical properties, as will be noted in this thesis. The energy difference between the lowest state in the conduction band and the highest state in the valence band is known as the band gap energy. A value for this energy difference will be noted in the discussion of optical properties.
b. **Bulk properties** The three bulk properties of interest in this thesis are the resistivity, the refractive index and the dielectric constant. The resistivity of diamond is in the neighborhood of $10^{15}$ ohm-cm, the crystal being a very good electrical insulator. A brief review of the results of measurements of the refractive index and the dielectric constant is given by Moss (2). All work quoted by him is in substantial agreement and the measured dielectric constant (5.68) is equal to the square of the zero frequency refractive index (2.38) as theoretically expected. Peter (3) has published the most recent investigation of the variation of refractive index with wavelength.

2. **Optical properties**

Until 1935, diamond was considered to have a single set of physical properties demonstrated by all samples. In that year, Robertson et al. (4) published their impressive research which showed that diamonds, on the basis of their optical absorption and photoconductive properties, could be divided into two categories, Type I and Type II. Type I diamonds absorb ultraviolet light with wavelengths less than 3000 A and infrared light in the wavelength region of 8 microns. Type II diamonds are transparent down to about 2200 A, and do not exhibit absorption in the 8 micron wavelength region. Since that publication by Robertson et al., a considerable amount of work has been done to check the
applicability of the two categories to all diamonds and to correlate other physical properties (mainly transport phenomena) with the typing of the diamond. The net result of this work is that the simple classification into two types is not sufficient to account for all the variations in properties of different diamonds. A new classification has been proposed by Champion (5), but it has not been sufficiently well tested that it constitutes a better typing of the diamonds. The old scheme persists, but with one alteration. Type II diamonds are now divided into Type IIa and Type IIb diamonds. Type IIa are the diamonds of the type Robertson, Fox, and Martin studied and called Type II. Type IIb diamonds are semiconducting diamonds discovered by Custers (6). These Type IIb diamonds have the same general absorption properties (some extra absorption occurs in the two to five micron infrared region) as Type IIa diamonds but their resistivities are orders of magnitude lower (10 to $10^8$ ohm-cm). Much current interest is being shown in these Type IIb diamonds but it is out of place to describe them further in this thesis.

In the following brief discussion of the optical and transport properties, the classification of Type I and Type IIa will be used where necessary or convenient. It has become evident from recent investigations that imperfections (impurities or structural faults) are responsible for many of the optical properties of diamond. Since different
imperfections may be present in varying amounts in different diamonds, it seems reasonable to attempt a classification into perfect diamond and imperfect diamond. These correspond very roughly to Type IIa and Type I respectively, but important differences will become apparent. This classification will be used in the organization of the presentation of optical properties. The properties of perfect diamond will be discussed first. The properties of imperfect diamond will be discussed by characteristic imperfection.

a. **Perfect diamond**

Perfect diamond is perhaps only a fictional term, but Type IIa diamonds come sufficiently close to its realization that they will be used as the identity in this thesis.

Optical absorption in perfect diamond occurs mainly in the ultraviolet and infrared regions. The ultraviolet absorption is due to the direct excitation of electrons from the valence band. The infrared absorption occurs in the region from three to five microns and has been shown to be lattice absorption (7). Reproductions, from published articles, of the ultraviolet and visible absorption for one Type IIa diamond and the infrared absorption for another Type IIa diamond are shown as Part A and Part B respectively in Figure 1. Part A is a figure from the article by Clark et al. (8). The figure shows the variation of the absorption coefficient with photon energy for Type IIa diamond. The absorption coefficient appears to rise steadily throughout
the visible range (about two to three ev) and the ultraviolet until, at about 5.4 ev it rises very rapidly with photon energy. \((W = \frac{1.2396}{\lambda}\) where \(W\) is the photon energy in electron volts and \(\lambda\) is the wavelength in microns.\) The absorption in the visible and near ultraviolet is known as the long-wavelength tail of the fundamental (band-to-band transitions) absorption region starting at about 5.4 ev. Several explanations (9) have been proposed for this tail, but none are particularly well substantiated. One of these explanations is in terms of imperfections. Assuming that this is a plausible explanation, one would say that even Type IIa diamonds are not examples of perfect diamond. The characteristics of a perfect diamond can probably be extracted from the Type IIa data by allowing the tail to decrease in magnitude. This extraction would leave only the fundamental absorption in the region of 5.4 ev. Analysis of the fundamental absorption spectrum yields a value for the band gap in diamond. Values reported in the literature are \(5.59 \pm 0.3\) ev (10), \(5.40 \pm 0.03\) ev (8), and \(5.43\) ev (11).

The lattice absorption bands in the infrared region are shown in Part B of Figure 1. This spectrum is a reproduction of Figure 1 from the paper by Blackwell and Sutherland (12). Note that the percentage absorption is plotted versus wavelength, in microns, in this case. The absorption structure is confined to the 2 to 6 micron region. The observed peaks are tabulated in the paper by Blackwell and Sutherland.
Part A. UV and Visible Absorption Spectrum of a Type IIa Diamond. Reproduced from Clark et al (8).

Part B. Infrared Absorption Spectrum of a Type IIa Diamond. Reproduced from Blackwell and Sutherland (12).

Figure 1. Absorption spectra of Type IIa diamonds.
b. Imperfect diamond Three optical systems are frequently observed in diamond. These systems are absorption bands and emission bands which often exhibit some structure. Each system appears to be associated with a different imperfection and will be treated separately in the following discussion.

Before the individual systems are discussed, the effect of imperfections on the absorption properties will be displayed. Figure 2 shows portions of optical absorption spectra of two different Type I diamonds. Part A is a reproduction of Figure 2 in the article by Clark et al. (8). Note that the abscissa and ordinate scales are different from those used for the Type IIa data shown in the previous figure, and that the scales of the upper and lower sections of Part A are different. Four absorption systems can be identified in Figure 2A. The three systems at low energy are centered at approximately 1.6, 2.7, and 3.2 ev, while only the edge of the highest energy system is seen rising at about 3.8 ev. Only the last three systems will be discussed in this section. Very little information is available on the lowest energy system. The structure associated with each system has been separated into absorption lines which are tabulated in the original article. Part B of Figure 2 is the reproduction of Figure 3 in the article by Blackwell and Sutherland (12). It shows the absorption spectrum of a Type I diamond. This is not the same diamond whose ultraviolet and visible spectrum
Part A. UV and Visible Absorption Spectrum of a Type I Diamond at room temperature (broken line) and at 80°K (full line). Reproduced from Clark et al. (8).

Part B. Infrared Absorption Spectrum of a Type I Diamond. Reproduced from Blackwell and Sutherland (12).

Figure 2. Absorption spectra of Type I diamonds.
is shown in Part A. Note that, in addition to the lattice absorption peaks observed in all diamonds, structure is present in the 7 to 11 micron wavelength region. The absorption lines are tabulated by Blackwell and Sutherland. Several other spectra from different Type I diamonds are given in the original article. On examination, it is obvious that the different lines in the 7 to 11 micron region can drastically differ in relative size in the various diamonds. The reason for the variation is that the lines are associated with different imperfections whose absolute densities vary among the different diamonds.

The highest energy system is characterized by the secondary absorption edge which begins its rise at about 3.8 ev (about 3300 angstroms) as seen in Figure 2A. The absorption coefficient continues to increase with increasing photon energy (past the largest energy on the figure) to the fundamental, band-to-band transition region at 5.4 ev where the absorption coefficient shoots up much more rapidly (10). In the region of 4 ev, absorption lines are superimposed on the edge. Several of the lines in the infrared region (7 to 10 microns in Figure 2B) have been shown (13) to be associated with the secondary absorption edge. Kaiser and Bond (14) have used this information in the execution of an experiment in which they have been able to show that an absorption line superimposed (at 4.1 ev) on the edge, and probably the edge itself, are manifestations of nitrogen present as a
substitutional impurity in diamond. Independent correlation of nitrogen as an impurity was obtained by Smith et al. (15). Since the presence of the secondary absorption edge and the infrared absorption in the 7 to 11 micron region is the basis for the classification of a diamond as Type I, the classification proposed by Robertson et al. distinguishes only between diamonds which are rather perfect, Type IIa, and those which have a considerable amount of impurity, Type I. Two other major systems, discussed below, are not considered in this typing. This exclusion may account for some of the difficulties encountered with this classification.

The absorption system centered at 3.2 ev is a very interesting system. It is often referred to as the 4150 angstrom system because the major line in its structure occurs at this wavelength. The absorption in this system appears (Figure 2A) to consist of discrete lines superimposed on a continuous band. The absorption lines in the 7 to 11 micron infrared region which are not associated with the secondary absorption edge are associated with the 4150 A system (13). Also, Raal (16) has recently made quantitative measurements of two absorption bands, centered at 2300 A and 2360 A in the ultraviolet close to the fundamental absorption edge. He concluded that there is a distinct possibility of correlation of these bands with the 4150 A system. The system is active in luminescence, accounting for the many references to blue fluorescence in diamond. The luminescence
occurs as fluorescence, phosphorescence, and thermoluminescence (17), and can be excited by light (with photon energy greater than about 3 ev), X-rays, electron bombardment, and friction. An interesting and as yet unexplained property of the system is the mirroring of the emission and absorption spectra in the main line at 4150 A. This mirroring is exhibited and discussed in the article by Dyer and Matthews (18). The line at 4150 A is common to both emission and absorption systems. Peaks with the same size relative to the main line occur at the same energy difference from the main line in the emission and the absorption spectra. However, the peaks are on the high energy side of the main line in absorption and on the low energy side in emission. The emission structure appears to be the mirror image (in energy) of the absorption structure. This 4150 A system occurs in both Type I and Type IIa diamonds, but it is much less prominent in the latter. No imperfection has yet been definitely associated with this system, but several proposals have been offered (5,18,19).

The remaining system at 2.7 ev is known as the 5032 A system. Its properties are quite parallel to the 4150 A system. Until very recently the 5032 A system was thought to be always accompanied by the 4150 A system. Gomon (20) has found a specimen in which this was not the case. The absorption spectrum of this system consists of discrete lines superimposed on a continuous band. The luminescence
The spectrum associated with this system has the same type of mirroring property as the 4150 Å system. The absorption is usually weaker than that for the 4150 Å system, but it has been observed in both Type I and Type IIa diamonds (18). High energy electron bombardment followed by heat treatment has been found to considerably enhance this system. Elliott et al. (21) have suggested that the imperfection causing this system consists of an interstitial carbon atom anchored to an interstitial impurity.

In summary, the optical properties of diamond may be divided into those associated with perfect diamond and those associated with imperfections in the diamond. Each imperfection generates characteristic optical properties. The system which includes the secondary absorption edge at 3.8 ev is caused by nitrogen entering the diamond lattice as a substitutional impurity. The other two systems at 4150 Å and 5032 Å are active in both absorption and luminescence. The properties of these two show some similarities and are quite puzzling. The origin of the 4150 Å system is unknown. The 5032 Å system is thought to be the result of a center consisting of an interstitial carbon atom anchored to an interstitial impurity atom.

3. Charge transport properties

This section is devoted to a brief review of the properties of electrical conduction induced in diamond by light and
by bombardment with nuclear radiation. One would like to discuss the observed properties and to correlate them with the optical properties discussed in the previous section. The former will be done, but the latter cannot be done at the present time. Attempts (4,22,23,24) have been made to correlate the optical and the electrical properties, but these have been only partially successful. It has been possible to conclude only that Type IIa diamonds tend to be better induced conductors than Type I. Champion (5) has attempted to correlate some of the transport properties with the 4150 A optical system and the 5032 A system. Very little experimental evidence is available to corroborate the correlation at present. It seems most plausible to consider all the known imperfections when attempting a correlation of optical and electrical properties. This is a formidable experimental task in the case of diamond, not only because the experimental measurements are rather difficult, but also because impurity content cannot yet be controlled. The correlation will not be attempted here.

a. **Charge carrier excitation** The determination of the charge transport properties of diamond is dependent on the observation of an electric current in the crystal. Application of a voltage across the faces of a diamond slab in the dark will not result in a readily measurable current because the conductivity of diamond is so low (about $10^{-15}$ mho cm$^{-1}$). The band theory of solids provides an explanation
of the low conductivity, and an indication of the way to increase it. The band gap energy, shown in Figure 1, is so large in diamond (about 5.4 ev) that thermal excitation of electrons from the valence band to the conduction band is a very improbable process. Therefore, only very few electrons are available in the conduction band to contribute to conduction when an electric field is applied. The equilibrium number of intrinsic carriers at room temperature is of the order of $10^{-29} \text{ cm}^{-3}$, if the electron and hole masses are equal to the rest mass of the electron. If, however, sufficient energy were supplied to some electrons in the valence band to allow them to make the transition to the conduction band, the extra charge carriers would cause an increase in the conductivity. Both ultraviolet light and nuclear radiation have the ability to supply the necessary energy to the electrons.

The increase in conductivity of diamond upon application of light is known as photoconductivity. Not all photon energies are equally efficient in inducing conductivity because not all photons are sufficiently energetic to cause band to band transitions. Moss (2) has reviewed the measurements of the variation of this efficiency (spectral sensitivity) with photon energy near the fundamental absorption edge. From these data he obtained a value of 5.3 ev for the band gap energy of diamond. Gudden and Pohl (25) have obtained photocurrents in the long wavelength tail of the
fundamental absorption edge to about 5000 Å. No bumps, which might be expected from extra charge carrier excitation from imperfection levels, are apparent in the sensitivity spectrum obtained by them.

Nuclear radiation bombardment of the diamond also produces an increased conductivity. The large amount of energy lost by alpha particles, beta particles, or gamma rays in the diamond is distributed to a number of the valence electrons, exciting them to the conduction band. The fundamental difference between nuclear-radiation-induced conductivity and photoconductivity is that nuclear radiation generates charge carriers in discrete pulses of very short duration, while photoconductivity is usually a steady state phenomenon.

Charge excitation is only the first part of the conduction process. The subsequent motion of the charge carriers in the applied electric field is the more interesting process. Electrons, once they are introduced into the conduction band do not necessarily move to the electrodes and through the external circuit. Impurities and other imperfections often have empty energy levels in the forbidden gap, as noted before. These levels, known as traps, tend to capture electrons (which prefer the lower energy state) as they drift past. Since trapped charges cannot contribute to conduction, the conductivity of a diamond is lowered by the presence of traps.

Only the excited electrons have been considered so far.
A major success of the band theory is the recognition that the vacant states in the valence band behave like positively charged particles. (For an explanation see, for instance, Kittel (1), p. 298.) The (actually fictitious) particles are called holes, and their contribution to the conductivity must be considered along with that of the electrons. These holes, like electrons, can be trapped. (An electron in a filled impurity level drops into the empty, lower energy state in the valence band leaving an empty state or hole in the impurity level.) Holes play an important part in the charge transport characteristics of diamond.

b. Photoconductivity characteristics Gudden and Pohl did the pioneering photoconductivity work, which is reviewed by Nix (26) and by Hughes and Du Bridge (27). Gudden and Pohl observed both primary and secondary currents whose properties will be discussed in order in the next paragraphs.

The primary current is that observed immediately after the exciting light is incident on the diamond. It is characterized by proportionality to the light intensity at all voltages, saturation for high electric fields, and rapid response to irradiation changes. The primary current was divided by the original investigators into negative and positive parts. The negative part was normally observed and was shown by Lenz (28) to be an electron current rather than a hole current. The positive part was elicited by shining red light on the diamond after ultraviolet light had been
applied for a few minutes. The red light under these circum-
stances produced a considerable photocurrent, while red light
applied before the ultraviolet would produce a negligible
current. The positive current was interpreted as a current
of holes liberated from traps by the red light. Space charge
or polarization effects from the trapped charges were observed
at high photocurrents or long times.

The secondary photocurrent makes its appearance after
some period of primary photoconduction, the period depending
on the individual sample. This secondary current is charac-
terized by slow response to changes in illumination, non-
proportionality to the light intensity, and time-dependence.
Robertson et al. (4) have observed secondary effects which
they call activation, and have studied the growth and decay
of this activation. Activation is the enhancement of the
photocurrent induced by light of one wavelength due to a
previous or concurrent illumination with light of another
wavelength. It is not clear that there is any fundamental
difference between "activation" and "secondary photocurrents".
These effects have not yet been satisfactorily explained.

c. **Nuclear-radiation-induced conductivity**

The pulsed type of conductivity induced by nuclear radiation has
already been contrasted with the steady state nature of
photoconductivity. Despite this difference, primary and
secondary effects are observed in both cases. The variation
of the counting rate (the number of observable conduction
pulses per unit time) with time shows both primary and secondary effects in this nuclear-radiation-induced conduction case. For a typical diamond, the counting rate is observed to decrease with time for the first few minutes of bombardment, then to level off at a low counting rate for a considerably longer period, and finally to increase to its initial (approximately) counting rate at which it remains as long as the bombardment and electric field are supplied. The durations of the various parts of the behavior are different for different diamonds. The secondary effect is the activation which is observed as the rise in counting rate after a period of counting. This activation has been investigated by Willardson and Danielson (29) and by Trott (30). The explanation of the effect is still incomplete.

The primary effect - the decrease and leveling off of the counting rate in time - can be qualitatively understood in terms of trapping of the charge carriers. This effect will be discussed further in the next section. Two characteristic transport properties, the mobility of the carriers (the drift velocity per unit electric field) and the mean free time of the carriers before trapping, can be determined from observations of the heights (31,32,33,34) and rise times (35) of the conduction pulses. Reported values vary drastically, but order of magnitude values are $1000 \text{ cm}^2 \text{ volt}^{-1} \text{ sec}^{-1}$ for the mobility of both holes and electrons, and $10^{-8}$ sec for the mean free time before trapping for each.
B. The Diamond as a Nuclear Radiation Detector

Since nuclear-radiation-induced conductivity is employed in the execution of the experiment reported in the body of this thesis, the diamond as a nuclear radiation detector or counter will be described in more detail in this section. The diamond counter is basically a solid ionization chamber, so the discussion of the production of a signal by the counter will be similar to the discussion of signal production in a gas ionization chamber as given, for example, by Rossi and Staub (36). The observations of the radiation detection properties of diamond which have been reported in the literature will be discussed after the theory of signal production has been presented.

1. Theory of pulse height

Consider the electrical circuit shown in Figure 3. An electric field, $E$, is set up in the diamond by the application of the voltage $V_0$ by a battery. The diamond has an electrical capacity $C_1$. The stray capacity of the input circuit is represented by $C_2$. The resistance $R$, which is much smaller than the diamond resistance, is the grid resistor for the input vacuum tube of the count recording equipment described in Section II B. When an ionizing particle, represented by the vertical dashed line in the figure, enters the diamond at a distance $x_0$ from the anode, $N_0$ electron-hole pairs are created along the path of the ionizing particle. The
Figure 3. The basic counting setup.

\( C_1 = \text{CAPACITY OF THE DIAMOND} \)

\( C_2 = \text{STRAY CAPACITY OF THE INPUT CIRCUIT} \)

\( R = \text{GRID RESISTOR OF FIRST VACUUM TUBE IN DETECTION EQUIPMENT} \)
electron-hole pairs are assumed to be created in a path which is parallel to the electrodes. The liberated electrons drift toward the anode and the holes drift toward the cathode under the influence of the applied electric field, $E_0$. In the following discussion only the electrons will be considered. The effect of hole motion can be readily taken into account at the end of the discussion. The motion of the electrons causes a pulse of charge to flow in the external circuit. The instantaneous current, $I$, is represented by $I(t)$ in the diagram. Part of this charge flows through $R$, creating an instantaneous voltage, $V$, ($V(t)$ in the diagram) across the component. The voltage, $V$, which can be detected by suitable electronic equipment, can be related to the motion of the electrons in the diamond by an application of energy conservation to the circuit. The energy supplied by the battery (or a power supply) is absorbed by the motion of the electrons in the diamond, by changes in the energy of the two capacities $C_1$ and $C_2$, and as heat in the resistor $R$. Therefore, the energy conservation equation for the circuit is

$$V_0 I dt = N_0 e E_0 dx + C_2 V dV - C_1 (V_0 - V) dV + 2V dV/R , \quad (1)$$

when written for a small element of time, $dt$, during which the electrons move a distance $dx$ and the voltage changes an amount $dV$. Since $E_0 = V_0/L$, where $L$ is the thickness of the diamond, Equation 1 holds only for the case of unpolarized diamond, because only in this case is the electric field
acting on the charge carriers equal to $E_0$. Division of Equation 1 by $V_0$ and rearrangement of terms gives

$$I \ dt = N_o \ e \ dx / L + (C_1 + C_2 + 2/R) \ V \ dV / V_0 - C_1 \ dV \ . \quad (2)$$

If $V$ is much smaller than $V_0$, as is usually the case, then Equation 2 reduces to

$$I \ dt = N_o \ e \ dx / L - C_1 \ dV \ . \quad (3)$$

The current $I$ is equal to the sum of the charge flowing through $R$ and the charge flowing to the capacity $C_2$. Since $I_R = V/R$ and $dQ_2/dt = C_2 \ dV/dt$,

$$I = V/R + C_2 \ dV/dt \ . \quad (4)$$

Substitution of Equation 4 in Equation 3 yields, if $C_1 + C_2$ is set equal to $C$,

$$dV + V \ dt / R \ C = N_o \ e \ dx / C \ L \ . \quad (5)$$

If the total time during which the electrons move in the diamond is much smaller than $RC$, then the second term on the left side of Equation 8 is negligible, and the equation may be integrated to obtain the maximum value of $V$, called the "pulse height", $V_m$:

$$V_m = N_o \ e \ X / C \ L \ , \quad (6)$$

where $X$ is the total distance the electrons move. In the actual case, both holes and electrons move, so Equation 6, modified for the motion of holes as well as electrons, is
where $X_+$ and $X_-$ are the distances moved by the holes and electrons respectively.

It is desirable to go still further and obtain expressions for $X_+$ and $X_-$ in terms of fundamental properties of the diamond. In a crystal such as diamond, in which trapping sites are present, all liberated electrons (and holes) do not travel the same distance. There is a statistical distribution of path lengths, and only a mean path length is observed from pulse height observations. For this situation $X_+$ and $X_-$ in Equation 7 can be taken as mean path lengths. In order to obtain expressions for the mean distances $X_+$ and $X_-$, one must make several assumptions which are discussed in detail by McKay (31). The major assumption is that the traps are distributed uniformly throughout the crystal. The derivation of the mean distance for electrons is given by Mott and Gurney (37). They obtain, in the symbols used here,

$$X_- = w_\gamma \left[ 1 - \exp \left( - \frac{X_0}{w_\gamma} \right) \right]$$

where $w_\gamma = \mu_\gamma E \gamma$ with $\mu_\gamma$ equal to the electron mobility and $\gamma$ equal to the mean free time an electron spends in the conduction band before it is trapped. $E$ is the electric field which causes the electrons to drift. The quantity $w_\gamma$ is known as the schubweg for electrons. The calculation of the mean distance for holes is analogous to that for electrons.
except that these holes are traveling in the opposite direction, so \( x_0 \) must be replaced by \( L - x_0 \) in the above expression. The mobility, \( \mu_+ \), and the mean free time before trapping \( \tau_+ \) for holes will, in general, be different, so the desired expression is

\[
X_+ = w_+ \left[ 1 - \exp \left( 1 - \frac{L-x_0}{w_+} \right) \right].
\]  

Substitution of expressions 8 and 9 in 7 results in the following expression for the total voltage signal across \( R \), i.e. the pulse height.

\[
V_m = \frac{N_0 e}{CL} \left( w_+ \left[ 1 - \exp \left( -\frac{L-x_0}{w_+} \right) \right] + w_- \left[ 1 - \exp \left( -\frac{x_0}{w_-} \right) \right] \right). (10)
\]

One should note that the pulse height is a function of the position at which the ionizing particle creates the electron-hole pairs. In the usual experiment, the pairs are created at different positions by different particles, so a distribution of pulse heights is observed. Use will be made of this fact in later discussions. At low applied fields, Equation 10 becomes

\[
V_m = \frac{N_0 e}{CL} (w_+ + w_-)/C L = \frac{N_0 e E (\mu_+ \tau_+ + \mu_- \tau_-)}{CL}. \quad (11)
\]

The voltage signal is strictly proportional to the electric field in this case. At high fields, the pulse height increases (by Equation 10) to a maximum or saturation value given by

\[
V_m = \frac{N_0 e}{C}. \quad (12)
\]
This saturation value is obtained with fields which are sufficiently high that the electrons and holes traverse the entire crystal without being trapped.

In the experiment reported in this thesis the counting rate is the primary observable. The relation between the counting rate and charge carrier motion in the diamond is therefore of interest. The counting rate may be defined as the number of voltage pulses detected per second by the detection equipment. The counting rate is, then, a function of the detection equipment as well as of the diamond counting ability. This fact is a result of electrical noise generated or picked up in the electronic detection equipment. Since this noise is present as pulses, a means of discrimination against these noise pulses must be provided. The discrimination is based on the fact that most of the noise pulses are smaller than many of the voltage pulses from the diamond. The detection equipment is made to be sensitive only to pulses with heights greater than a certain minimum higher than all (or almost all) of the noise pulses. The counting rate is then the number of voltage pulses per second with heights greater than this minimum. Since there is a distribution of pulse heights from the diamond, the counting rate is related to the schubweg and therefore to the electric field. A larger electric field results in larger pulse heights, so more pulses have heights greater than the minimum set by the noise. The result is a higher counting rate.
With high electric fields in the diamond, all pulses have the maximum pulse height given by Equation 12. The counting rate in this case is independent of electric field and is equal to the number rate of incidence of ionizing particles on the diamond.

These above considerations apply only to the ideal case. In the actual case, conditions may be quite different. Pulse heights will vary because each ionizing particle does not create the same number of electron-hole pairs, because the trap distribution is different in different parts of the diamond, or because the electric field is different in different parts, to cite a few examples. The basic framework of the theory of pulse heights is still valid however and serves as a means of understanding the process of count production.

2. Properties of the diamond counter

The properties of the diamond as a detector of nuclear radiation can be best illustrated with a description of the behavior of the counting rate of a "typical" diamond in time. Typical is used in a very restricted sense here, since only about 2% of all diamonds possess the ability to "count" or to detect nuclear radiation. However, the behavior to be described is typical of those diamonds which do count.

a. Counting with an applied field  Consider the typical diamond in the experimental setup illustrated in
Part A of Figure 4. The voltage $V_0$ (supplied by the battery) provides an electric field $E_0$ in the diamond. A gamma ray passing through the diamond interacts with the carbon atoms creating high energy electrons. These high energy electrons create electron-hole pairs which are separated by the field. For simplicity, the gamma ray is shown to directly create the electron-hole pairs in Figure 4. The electrons move to the left in the figure and the holes to the right under the influence of the field. These holes and electrons move until they become trapped. Due to the motion of electrons and holes in the diamond, a current pulse is present in the external circuit as explained in the last section. The current pulse in the resistor $R$ creates a voltage pulse which is detected by the count recording equipment. If gamma rays are continuously incident on the diamond, then a certain counting rate will be detected. This counting rate is dependent on the number of traps in the diamond, the gamma radiation flux, the applied field, and the detection equipment.

b. Growth of internal polarization If gamma radiation bombardment is continued, the counting rate decreases, even if the gamma radiation flux is constant in time, as it is here. This counting rate decrease is generally assumed to be caused by the growth of an internal field, $E_1$, which opposes the applied field as shown in Part B of Figure 4. The trapped holes and trapped electrons, which are spatially displaced from one another, produce the internal field.
Figure 4. Count production under different electric field conditions.
Since the internal field opposes the applied field, the net electric field effective in causing the drift of gamma-ray-liberated electrons and holes is smaller than the applied field. The effective field \( E_e \) is assumed to be

\[
E_e = E_0 - E_1. \tag{13}
\]

The internal field \( E_1 \) may not be uniform in the diamond, so \( E_e \) may not be uniform also. However, the fields will be considered uniform throughout the qualitative description to be given. The pulse height, given by Equation 10, is decreased from its initial value because the schubwegs, \( w^- \) and \( w^+ \), are smaller as a result of the smaller effective electric field. The decrease in the pulse heights is reflected, in the general case, in a decrease in the counting rate.

c. Counting with an internal field When the internal field is present in the diamond, as evidenced by the decreased counting rate, the applied field may be removed as shown in Part C of Figure 4. The internal field will persist because the holes and electrons are trapped. The free holes and electrons generated by the passage of a gamma ray in this situation will move under the influence of the internal field \( E_1 \). The holes will move to the left and the electrons to the right in this case so the voltage pulse across the resistor \( R \) will have a polarity opposite to that of a voltage pulse under the applied field conditions. With the gamma ray flux incident on the diamond, a counting rate will be
detected. An internal field counting phenomenon in diamond was first reported by Wooldridge et al. (38).

C. Essence of This Investigation

1. Purpose

The purpose of this investigation was to study the energy levels of the trapping centers in diamond, i.e. to determine where in the forbidden energy gap the trapping levels lie. This is a fundamental problem in semiconductor and insulator research since the electrical charge transport properties depend critically on the trapping processes. Trapping levels are also believed to be active participants in some luminescent phenomena. Probably the most important characteristic of a trapping center from the transport point of view is the capture cross-section, but the energy level is also important for a determination of the equilibrium occupations of these levels, the prediction of transient behavior, and the possible identification of the trapping center.

It is necessary to define the term "trapping center" as it will be used in this work. It should be noted that at any instant of time, any discrete energy level in the forbidden gap might act as a trap depending on its state at that instant. For example, a normally filled energy level may be ionized at a certain instant of time. This level will
act as a trap for electrons at this instant. To denote every energy level in the gap as a trapping level is strictly correct, but it is not necessarily physically significant. It is more common to designate the energy level by its predominant function. In the language of semiconductor physics, the primary function of donor levels is to donate their electrons to the conduction band and not to act as electron or hole traps, depending on their instantaneous occupation. A trapping center is defined as a region of the lattice which has an affinity for one sign of charge and which has for its predominant function the capture of a charge carrier of that sign. This definition excludes donors and acceptors, as the terms apply to semiconductors, but does not exclude recombination centers. A recombination center is a region of the lattice which serves as a center at which electrons and holes may recombine. Since recombination centers are double traps, i.e., they trap first one sign and then the other sign of charge in a steady state situation, it is probably fitting that they should be included in the general definition used here.

2. Previous work in this field

Willardson and Danielson (22,29) did extensive work on diamond in an attempt to better understand the counting process and to correlate the counting property with optical properties. Part of their research was devoted to a study of
the decay of the counting rate under internal field conditions, as explained in Section B-2-c. This decay was observed under several different conditions among which were concomitant illumination with violet light and with red light. The decay was much more rapid when the diamond was illuminated than when it was in the dark. This brief study was the initial investigation of which this thesis is a continuation. G. C. Danielson suggested that a logical experiment was to measure the decay rate of the internal field counting rate when infrared radiation in the 1 to 5 micron region was shone on the diamond. Shallow traps in diamond would be studied by this experiment. R. B. Horst attempted this experiment, but he found that the infrared had little effect on the decay. D. E. Hudson then suggested that a careful study in the visible and near infrared regions would be useful to determine the role of deeper traps in the generation of an internal field. Horst, working under the direction of Hudson made the preliminary study. Horst (39) studied two diamonds at wavelengths 100 millimicrons apart from 300 to 1,000 millimicrons. He found that the decay rate increased with decreasing wavelength, but he was unable to get any quantitative results. He found very little effect of intensity at the two wavelengths he used for this observation. These preliminary studies laid the groundwork for this present investigation.

Chynoweth (40) used a Nernst filament at different
intensities to obtain a decay of the space charge in a diamond. He obtained some decay curves which approached an exponential dependence for high intensities. Again the results were mainly qualitative. Champion and his group at King's College in England have studied diamond in detail. Their studies of photoconductivity (41) and bombardment conductivity (30, 41) as functions of temperature resulted in the assignment of thermal liberation energies of 0.5, 0.6, 0.8, and 1.0 eV to the trapping levels. Some qualitative data were taken using red and white light. They further presented some evidence for the nonequivalence of the thermal and optical liberation energies. Bull and Garlick in a study of thermoluminescence observed a trap depth of 0.7 eV.

3. General method

This experiment was designed to measure in a more direct manner the energy levels of the various trapping centers in diamond. The basic experiment consisted of two steps. The first step was the creation of an internal electric field, $E_1$, in the diamond by bombardment with gamma rays, as discussed in Section B-2. This internal field was generated by the spatial displacement of trapped holes from trapped electrons. The second step in the basic experiment was to remove the applied field and to shine in monochromatic light of a known wavelength and intensity. This light caused a decay of the internal field by liberating trapped carriers.
which upon liberation moved across the diamond to neutralize their charge opposites. The amount of remaining internal field was measured in terms of a counting rate in a way to be described. This basic experiment was repeated with several intensities of various wavelengths of light. The purpose was to study, as a function of wavelength, the ability of the light to liberate trapped charges: i.e., to study the cross section for liberation. The wavelengths at which the cross section increased rapidly would presumably correspond to the difference in energy between the trapping level and the edge of the band in which the liberated charge is mobile. The variation of the internal field decay rate with photon intensity was required in order to refer the decay data at the various wavelengths to a common photon flux for the observation of cross sections.

The counting property of diamond was used not only to create the internal field but also to detect its presence. Under applied field conditions, a decrease in counting occurs, as noted in Section B-2. The amount of decrease from the initial counting rate was a rough measure of the amount of internal field present in the diamond. After the removal of the applied field, the counting rate was the observable which was used as a measure of the internal field in order to detect the decay of this internal field. The rate of liberation of trapped charge was reflected in the rate of decay of the internal field, which in turn was measured by the change in
the counting rate with time. Since the effect of controlled light on the decay was desired, and since gamma rays also cause a decay of the internal field, the diamond was shielded from the gamma radiation except for short periods of time during which the counting rate was used as a probe of the internal field. These probes were made at intervals such that the effect of the nuclear radiation was negligible in comparison with that of the light.

The variation of the internal field counting rate with time was also observed before the diamond was illuminated. Any spontaneous decay of the internal field was noted during this period. The probing technique described above was used during this dark period also.

This experiment is the first designed to measure directly the liberation of trapped charges by controlled illumination. Most experiments reported in the literature measure the effect of the liberation of trapped charges on the applied field counting rate. It is difficult to separate the effect of polarization and the effects of increased or decreased trapping in the applied field experiment. No reported experiment on trapping effects in diamond has been done with controlled illumination, so only qualitative effects of light have been found.

4. **Advantages of the method**

The greatest advantage of this method over those reported
above is that a more direct study of the detrapping process is made in this case. Another advantage is the completely internal nature of the observation. No charges are required to pass through the diamond-electrode barrier layer for the observation of the signal. This feature eliminates the bothersome surface effects which plague many measurements. Furthermore, the method is quite sensitive; only $3 \times 10^9$ electron hole pairs need be separated and trapped near the electrodes for each square centimeter of electrode surface area in order to establish a readily observable internal field of the order of $5 \times 10^3$ volts per centimeter.
II. INSTRUMENTATION

A. Introduction

The counting rate is the primary observable of the experiment, so it is not surprising to find that much of the equipment is that utilized in a nuclear physics experiment. The theory of the basic counting process has been presented in the Introduction. Requirements of the apparatus for the detection of the pulses will be discussed in the first part of this section. The discussion of requirements will be followed by a description of the apparatus.

1. Apparatus characteristics for pulse detection

The successful detection of the voltage pulses generated across resistor $R$ in Figure 3 (Section I-B) by the current pulses from the diamond requires the amplification of the pulse by an electronic circuit. This circuit, a pulse amplifier, must have certain gain characteristics for a certain band of frequencies to be useful in the detection process. This section is intended only to discuss briefly the effect of the amplifier on the shape of the voltage pulse, and to estimate the required gain of the amplifier. The shape of the voltage pulse developed across $R$ will be discussed first. Then the effect of the amplifier on this shape will be described. Finally, the gain required of the amplifier will be estimated.
In Section B of the Introduction, the size of a voltage pulse produced by nuclear bombardment of the diamond was derived (Equation 10). In that derivation, one of the approximations was that the total time during which liberated charges move under the influence of the electric field was much smaller than RC, where R is the resistor across which the voltage signal is developed, and C is the sum of the capacity of the diamond and any stray capacity in parallel with the resistor. That this approximation is reasonable for the components used in this experiment can be demonstrated by the following rough calculation. The transit time, \( T_t \), for a charge carrier to move completely across the diamond is

\[
T_t = \frac{d}{v},
\]

where \( d \) is the thickness of the diamond and \( v \) is the drift velocity of the charge carrier. The drift velocity of a charge carrier in an electric field \( E \) is \( \mu E \), where \( \mu \) is the mobility of the charge carrier. In diamond the mobility of both holes and electrons is about \( 10^3 \text{ cm}^2 \text{ volt}^{-1} \text{ sec}^{-1} \). A low value of the applied field will result in a high value for the transit time and an unfavorable condition for which the approximation under test holds. Such a low value of the field would be \( 10^3 \) volts cm\(^{-1}\). The transit time for the maximum thickness of the diamonds used in this experiment, 0.06 cm, is \( 6 \times 10^{-8} \) seconds. This value may be taken as a high estimate of the time during which liberated charges move in the diamond. The resistor \( R \) had a value of 40 megohms.
in this experiment. A reasonable estimate of the capacity $C$ is 8 picofarads. The value of $RC$ is therefore $320 \times 10^{-6}$ seconds. The approximation is very good in this case.

The shape of the voltage pulse across the resistor $R$ can be estimated with the aid of the calculations in the preceding paragraph. The transit time argument suggests that the voltage pulse across the resistor $R$ attains its maximum value, $V_m$, in the order of $10^{-3}$ seconds. To obtain the shape of the pulse after the maximum, one must determine the dependence of the voltage after the charge carriers have stopped moving. This dependence can be obtained from Equation 8 in Section I-B. When the charge carrier motion has ceased, the right side of that equation goes to zero. The equation then becomes

$$dV = - V \frac{dt}{RC}.$$  \hspace{1cm} (14)

The solution of this equation appropriate to the existing conditions is

$$V = V_m \exp \left(- \frac{t}{RC}\right).$$  \hspace{1cm} (15)

where $V_m$ is the value of the voltage across the resistor when the charges stop moving, i.e. the maximum value of the voltage pulse. The voltage decays exponentially with a time constant equal to $RC$. Since $RC$ is about 320 microseconds, the decay is very slow with respect to the growth. On a time scale of the order of 1 to 10 microseconds the voltage pulse appears to be a step function.

The shape of the voltage pulse after amplification was
quite different from the input pulse shape. This is a common occurrence with fast rising pulses. An amplifier responds in a finite time to the application of a step function to the input. The time required for the amplified pulse to increase from 10% to 90% of its full value when a step function is applied to the amplifier input is often used as a measure of the speed of response of the amplifier. This time is known as the rise time of the amplifier and is determined by circuit components and construction details. For the amplifier used in this experiment, the rise time was about one microsecond. Since the voltage pulse applied to the input of the amplifier was essentially a step function on the microsecond time scale, the amplified pulse rose to its maximum value in about one microsecond. The decay of the amplified voltage pulse was also determined by the amplifier. The time constant of the decay of the amplified pulse was equal to the value of the smallest time constant associated with the coupling circuits in the amplifier. In the amplifier used in this experiment, this time constant was set at one microsecond. Therefore, an amplified pulse due to diamond conduction rose to a maximum amplitude in about one microsecond and decayed with a time constant of one microsecond. Gillespie (42) has shown that this equal time condition results in the maximum signal-to-noise ratio.

The gain required of the amplifier may be estimated in the following manner. The maximum signal to be expected from
the diamond is given by Equation 12 in Section I-B. The expression is

\[ V_m = N_0 e / C \]

where \( N_0 \) is the number of electron-hole pairs formed by each ionizing particle, and \( C \) is the sum of the capacity of the diamond and the stray capacity in parallel with the resistor \( R \). It is obvious that the stray capacity should be reduced as much as possible to obtain a large signal. One may estimate the size of the maximum signal to be expected if \( N_0 \) is known. This number is equal to the product of the energy of the gamma ray and the reciprocal of the mean energy required to form an electron-hole pair. Kennedy (43) has found that 18 ev are required on the average to form each electron-hole pair. Then, with a 1.33 Mev incident gamma ray and a total capacity of 8 picofarads, the maximum voltage signal, \( V_m \), is given by

\[ V_m = \frac{(1.33 \times 10^6)(1.602 \times 10^{-19})}{(18)(8 \times 10^{-12})} = 1.48 \times 10^{-3} \text{ volts.} \]

The minimum amplified voltage pulse which would register as one count in the apparatus has an amplitude of five volts. The amplifier must therefore have a minimum voltage gain of about \( 3 \times 10^5 \). The lower limit of detection is set by the noise level of the system.

2. Preview of the equipment

The instrumentation to carry out the proposed experiment
can be divided into three major parts: the basic counting system, the count recording equipment, and the source of controlled illumination. Figure 5 illustrates the experimental setup in block diagram form. The setup consisted of the three major parts listed above plus some auxiliary equipment not shown in the diagram. The apparatus to be described here was that used in the major portion of the experiment. This will be known as Apparatus II. A slightly different setup, Apparatus I, was employed in a preliminary study and is described in Appendix A.

B. The Individual Components

1. The basic counting system

Figure 6 shows the basic counting system. This system was the source of the voltage whose rate of occurrence was the major observable of the experiment. Individual gamma rays generated in the system were converted to small voltage pulses which appeared at the output of this system. The conversion mechanism has been explained previously. The system consisted of a source of gamma rays, the diamond in its holder, a source of high voltage, and a switch which allowed one electrode on the diamond to be either at high voltage or at ground potential.

a. Source of gamma rays  Cobalt 60 was the source of gamma rays. Two gamma rays of energies 1.17 and 1.33 Mev are emitted in the decay which occurs with a half-life of
Figure 5. Block diagram of experimental setup.
Figure 6. Block diagram of the basic counting system.
about 5.2 years. The radioactive material was encapsuled in a brass cylinder one inch long and one quarter inch in diameter. The indicated strength of the source was 0.56 milli­curies on September 1, 1960.

The use of the gamma source only as a probe during the internal field decay necessitated a mechanism to move the source between a shielded and an unshielded position with respect to the diamond. The unshielded position had to be reproducible to the extent that the same average flux of gamma rays was incident on the diamond whenever the source was brought to its unshielded position. This was accomplished by causing the source cylinder to traverse a copper tube mounted vertically to one side of the diamond holder. A stop at the bottom reproducibly positioned the source one inch from the diamond. The relation of these components is shown in Figure 9 in Section II-C. A lead block was mounted at the upper end of the copper tube. The source was drawn by a silk thread up into a hole in the lead block where it was shielded from the diamond. A grooved wheel mounted above the lead block converted the linear motion to rotational motion for convenience.

b. Diamond holder The diamond holder was the center of activity of the experiment. This component held the diamond, made electrical contact to it, and allowed both light and gamma rays to be incident on it. Figure 7 is a drawing of the holder. The diamond (d) was held between a
Figure 7. The diamond holder.
NESA* glass plate (a) and a copper foil electrode (b). The one-half inch by one-half inch NESA glass plate was clamped in a supporting metal structure (c) which attached to a Plexiglas sheet (e). The metal frame also served as an electrical contact to the NESA plate. The copper foil electrode was supported by a piece of Teflon (f), also attached to the Plexiglas sheet. Since the copper foil electrode was cut to the size of the diamond face, a different electrode was used for each diamond. The diamond was held in place by a slight pressure exerted by the strained Teflon.

c. High voltage supply and electrode potential switch
The source of high voltage was the electronic circuit supplied with the scaling unit employed in the count recording system. The supply was continuously variable between 400 and 2,000 volts D.C. with a regulation of 0.01% per percent change in line voltage from 95 to 135 volts. Extra filtering for high frequencies was added to the output. The electrode potential switch was a four pole ceramic switch specifically designed for low leakage.

2. The count recording equipment
This equipment amplified the small voltage pulses which appeared at its input and recorded the presence of a pulse if its amplitude were greater than a preset minimum. A

---

*Trade name (Pittsburgh Plate Glass Co., Pittsburgh, Pa.) for glass coated on one side to make it electrically conductive.
modified Bell-Jordan linear amplifier and its normal preamplifier, a pulse height discriminator, and a scaler comprised this system.

a. The amplifier and preamplifier The amplifier and preamplifier were required to amplify the input voltage pulses from their microvolt range value to the level of volts at which the discriminator circuit could operate. The modified Bell-Jordan amplifier and preamplifier had a measured gain of about $6 \times 10^4$. The amplifier was modified to make its differentiating time constant about equal to the integrating time constant of one microsecond. The heaters of the preamplifier vacuum tubes and the amplifier input vacuum tube were powered from a dc supply in order to further decrease the noise. Care was taken in shielding and grounding these circuits, but even with these precautions the R.M.S. noise level was of the order of 70 microvolts.

b. Pulse height discriminator This component generated a standard pulse for each incoming voltage pulse greater than some minimum value which was set sufficiently high that most of the noise pulses would not qualify. The amplitude of the standard pulse was independent of the amplitude of the incoming pulse. The output pulse was a square-topped pulse with an amplitude of 10 volts and a pulse width dependent on the width of the input pulse. The experimental data were obtained with a discriminator setting corresponding to a minimum triggering pulse of about 7.5 volts.
c. **Scaler** Each pulse generated by the discriminator was counted by the scaler. The scaler used was the Nuclear Instrument and Chemical Corporation's Model 162 scaling unit. This model has a resolving time of two microseconds and required a voltage pulse of amplitude 0.25 volts to record. A switch provided a choice of the number of counts which were recorded as a unit on the mechanical register. A bank of neon lights interpolated between units. A Standard timer (Model S100), activated by the count initiating switch, recorded the length of the counting period.

### 3. **The source of controlled illumination**

Steady monochromatic illumination of known wavelength and intensity was required for the decay portion of the experiment. This illumination was obtained from the system composed of the monochromator with its light sources, a mirror and indexing mechanism, and the photoelectric cells and their associated equipment.

#### a. **The monochromator and light sources**

A Bausch and Lomb 250 millimeter focal length grating monochromator with two primary light sources was used to provide monochromatic light. The instrument provides a monochromatic image of the grating focused about 60 millimeters from the exit lens. This image is square and about 12.5 millimeters on a side. The wavelength of the desired monochromatic light was set on a control which was continuously variable between 200 and 1200
millimicrons. The spectral purity of the emergent beam was controlled by slits at the entrance and exit lenses. These slits also controlled the intensity of the beam. One of the primary sources was a Hanovia-type mercury arc source which was supplied with the monochromator. Since its spectrum consists of discrete lines in the visible and near ultraviolet region, the spectral purity of the beam was determined by the normal width of this line as long as the slits were not wide enough to allow two adjacent lines to be focused. The slit widths could thus function well as intensity controllers for this source. The other primary source was a 1,000 watt incandescent projection lamp which was used to provide light at wavelengths unattainable with the mercury arc source. Any variation of the slit widths in this case would result in a change in spectral purity as well as in intensity. For this reason the intensity was controlled by limiting the power to the lamp by means of a Powerstat while the slit remained fixed. The higher orders of monochromatic radiation from the grating were removed from the emergent beam by appropriate glass filters.

b. The mirror and indexing mechanism

In order to eliminate any discrepancy in the reflection factor of the mirror in the intensity determination, the mirror was present in the optical path of the monochromatic beam at all times. Figure 8 is a photograph of the mirror and supporting structure as they appear in Apparatus II. A front-surfaced
Figure 8. Photograph of the mirror and support structure in the experimental setup.

Key:
- g mirror
- h mirror mount
- j axle for mirror rotation
- k output lens of monochromator
- m photocell
- n diamond holder
aluminum mirror (g) was set at 45 degrees to the emergent beam from the monochromator's output lens (k). The mirror was attached by the mounting structure (h) to an axle (j). This axle was adjusted to be coincident with the axis of the emergent beam from the monochromator. The support for the mirror and axle was indexed so that the monochromatic beam was directed to positions 90 degrees apart in the plane perpendicular to the original beam. In the position shown in the figure, the mirror directs the light beam to the photocell (m). A ninety-degree rotation of the mirror to the next index position causes the beam to be directed to the diamond in the diamond holder (n). With the diamond holder and the photocell located at equal distances from the mirror, the same intensity was incident on each. Adjustments provided for proper alignment.

c. The intensity measuring device

The sole purpose of this device was to determine the intensity of the monochromatic illumination incident on the diamond. This is, of course, not a simple problem when the absolute intensity for a number of wavelengths is desired. The solution was to measure the intensity in the spectral range from 300 to 600 millimicrons with an RCA 929 photocell, and that in the range from 600 to 1100 millimicrons by an RCA 925 photocell. These photocells were later calibrated against another pair of the same types which had been calibrated for relative spectral sensitivity by the National Bureau of Standards. This
calibration is explained in Appendix D. All four photocells were masked with Aquadag and black electrical tape except for a clear window approximately five-eighths of an inch square. In addition, a type K2 gelatin filter covered the windows of the 925 photocells whose stability is disturbed by ultraviolet radiation.

An RCA dc microammeter (Model WV-84A) was used to measure the photocell current. This instrument is a stable battery operated vacuum tube ammeter with decade current ranges from ten millimicroamperes to one milliampere full scale. Its least count is two one-hundredths of full scale. On all ranges, the maximum voltage drop across the terminals is one half volt. The voltage sensitivity of the meter was calibrated and found to be within four percent of the true value at each major division of the scale. No current calibration was performed, but the same meter was used for all photocell measurements including the calibration. A check on the accuracy of the current measurement was obtained by measuring the photocell current developed by a photocell subjected to constant illumination with both the normally used instrument and a standby meter of the same type. The measured values agreed within one percent on the lowest and highest ranges used in the experiment.

A battery pack with a nominal value of 247.5 volts supplied the power for the photocells. The photocell and microammeter were connected in series across this battery pack.
4. **Auxiliary equipment**

A Tektronix type 531 oscilloscope with a type 53B plug-in unit was used to monitor the amplified pulses from the diamond counter. It was also utilized for testing and maintaining the equipment.

A minute timer manufactured by Precision Scientific Company was employed as an indicator of elapsed time during the internal field portion of the experiment. The least count of this timer was one one-hundredth of a minute.

A Streeter-Amet Scientific Counter employing a Microflex timer served as an automatic readout device for the applied field portion of the experiment. This device printed on paper tape at predetermined time intervals (in this case five minutes) the total number of pulses put out by the scaler during the preceding interval. Each pulse corresponded to one unit recorded on the mechanical register of the scaler. Each unit equalled 32 counts.

The amplifying equipment, scaler, high voltage power supply, and the light sources were all powered from a two kilovolt-amp Sorensen A.C. voltage regulator.

**C. The Assembled Apparatus**

All components of the basic counting system (with the exception of the high voltage supply), the preamplifier of the counting equipment, the photocell and battery pack, and
the mirror with its indexing assembly were enclosed in a large metal box which was attached rigidly to the monochromator. This box, known as the head box, was made light tight with respect to any stray light, and was painted with a flat black lacquer inside. The head box further served as an electrical shield for the circuitry housed within it. The preamplifier along with the input circuit were further shielded, by a copper foil structure, from electrical noise generated inside the box.

The relationship of the diamond to the gamma source, the mirror, and the photocell is shown in Figure 9. The center of the mirror, the center of the photocathode of the photocell, and the diamond were all located in the same plane, parallel to the plane of the paper. The gamma source guide tube was situated roughly in this same plane.

All of the electronic equipment rested on a large copper sheet covering the working area of a laboratory bench. This copper sheet was grounded to the distilled water pipe in the laboratory. A major source of noise - the signal transmitted by radio station WOI - was eliminated by this technique.
Figure 9. Schematic view into head box from monochromator position.
III. PROCEDURE

The total procedure employed in this experiment can be divided into two parts. The first part, described in Section A, is the procedure employed in the preparation of the sample and in the preliminary tests of the apparatus and the sample. The second part, described in the remainder of the section, is the procedure which composed a complete run, and which therefore was repeated for each run.

A. Sample Preparation and Preliminary Testing

The procedure to be described in this section was employed each time a diamond was loaded into the apparatus. The purpose of these steps was to assure the author that the equipment and the diamond were acting properly.

The first test was designed to make certain that the diamond holder, described in Section II-B, would not contribute any spurious pulses to the counting rate of the diamond when the main experiment was undertaken. A piece of Teflon of approximately the same size and shape as the diamond to be investigated was carefully cleaned in a solution of warm water and detergent. The piece was then rinsed in distilled water and in methanol. Thereafter it was handled only with tweezers. This careful cleaning was necessary because the piece of Teflon was to be subjected to high voltage and any electrical discharge across the surface would invalidate the
test. The Teflon "diamond" was inserted in the diamond holder and subjected to a voltage about 20% greater than that to be applied to the diamond in the main experiment. The monitoring oscilloscope was observed for breakdown pulses, which would indicate electrical discharge across parts of the diamond holder. No breakdown pulses were observed. The gamma source was lowered to its unshielded position one inch from the diamond, and the amplifier output was again monitored with the oscilloscope. The absence of any extra pulses due to the gamma source indicated that the diamond holder was working properly.

After this test was completed, the diamond was carefully cleaned by the same procedure used to clean the piece of Teflon. Particular attention was paid to the irregular edges of the diamond. Dirt or grease in crevasses on the edge could easily lead to discharge when the full voltage was applied. After it was cleaned, the diamond was handled only with tweezers. The piece of Teflon was removed from the diamond holder. The copper foil electrode of the diamond holder (b in Figure 7) was painted with Aquadag. While the Aquadag was still wet, the diamond was set on it and the diamond holder assembled. The Aquadag insured that good electrical contact was made to the diamond. The voltage which was to be used in the main experiment was applied to the diamond, and the amplifier output was again monitored for evidence of breakdown. If breakdown pulses were observed,
the diamond was recleaned until no breakdown was observed. The diamond was then ready for investigation.

B. Creation of an Internal Field

The first requirement for the execution of the basic experiment was the creation of an internal field in the diamond by the separation and trapping of electrons and holes. The phenomenon of pulsed conduction induced by nuclear particle bombardment was used to create this field in the manner described in Section I-B. This section is devoted to a description of the procedure employed in the creation of the internal field. This portion of the experiment is known as the applied field counting portion.

During an equipment warmup period of one-half hour the apparatus was checked for gross malfunctioning. Also during this period, the high voltage was set at a value which, when applied, would produce an applied field of 10 kv/cm in the diamond. The NESA electrode was at ground potential during this warmup period. The process of pulsed conduction, which resulted in the creation of the internal field, was initiated in the following manner. The high voltage was applied across the diamond through the electrode potential switch (Figure 6). Immediately after the voltage application, the following operations were performed in rapid succession: the gamma source was lowered to its counting position about one inch
from the diamond, and the scaler and automatic readout device were started. Rapidity in the performance of these operations was only essential for the observation of a fast decay in the applied field counting rate. The order of the operations was that for which a minimum of extraneous noise "counts" would be recorded. The amplified conduction pulses were counted by the scaler and were monitored by the oscilloscope to insure that the pulses being counted by the scaler were diamond pulses. During the initial two and one-half minute counting period, the total number of units (1 unit equals 32 counts) indicated on the scaler's mechanical register were recorded by the operator at thirty second intervals. At the two and one-half minute mark, the automatic readout device printed the total number of units accumulated since the initiation of the counting process. The device then reset to zero and began to accumulate the units for the subsequent five minute period. At the end of this five minute counting period the device again printed the accumulated units. The automatic device recorded the five-minute unit totals for the remainder of the hour-long applied field counting portion of the run. Checks were made on the accuracy of the printout device at several times during the run. These checks consisted of the comparison of the running total of units exhibited by the scaler's mechanical register and the sum of the five-minute totals printed by the automatic device.
At a printout time close to an hour after the run was started, the scaler was stopped. The electric field was left applied to the diamond, and the gamma source remained in its counting position. The diamond was thus left in its applied field counting condition, but the counts were not recorded. During the preceding hour of gamma-ray-induced conduction, the diamond had acquired an internal field of sufficient magnitude that the remainder of the basic experiment could be attempted. The situation in the diamond was that depicted in Part B of Figure 4 in Section I-B.

C. Decay of the Internal Field

The second part of the basic experiment was the observation of the decay of the internal field created by the procedure described in the preceding section. This part of basic experiment was the major part with respect to the purpose of the experiment. The rate of decay of the internal field, when light was applied to the diamond, was expected to be a measure of the effectiveness of the light in liberating the trapped charges which generated the internal field. The decay of the internal field was reflected in the decay of the counting rate when only the internal field was present in the diamond. The decay of the counting rate was observed first with the diamond in the dark to establish the dark decay rate. The dark decay rate was observed not only because it represented
data on an interesting phenomenon, but also because the decay rate could be used to correct the subsequent light-induced, or photon-induced, decay data.

The procedure employed to observe the internal field decay can be divided into three parts: the transition from applied field to internal field conditions, the observation of the dark decay, and the observation of the photon-induced decay. These procedures will be discussed in order in the following paragraphs.

1. **Transition from applied field to internal field conditions**

   This transition was the change from the situation depicted in Part B of Figure 4 (p. 29) to that depicted in Part C. The object of the procedure was to make the transition rapidly, in order to be able to observe a fast initial decay of the counting rate if such a decay occurred. The following procedure was employed in the transition. At the start of the transition the high voltage was still applied across the diamond and the gamma source was still in counting position. A few seconds before the transition was initiated, the amplifier polarity was switched to accept negative pulses. To initiate the transition, the operator rotated the electrode potential switch (Figure 6 in Section II-B) to the position which grounded the NESA glass electrode. This action removed the applied field from the diamond, and left only the internal field generated by the trapped holes and electrons.
Immediately after the electrode was grounded, the minute timer and the scaler were started in that order. The order was important. Execution in the reverse order would allow switching noise to be picked up by the amplifier, and possibly to be recorded by the scaler as extra counts. The gamma source remained in its counting position throughout the transition, so the diamond began to count under the influence of the internal field as soon as the transition was initiated. Thirty seconds after the initiation of the transition, the scaler was stopped, and the gamma source was raised to its shielded position. Again the order of the operations was that required to insure that extraneous pulses from noise (in this case microphonics) would not be recorded as counts. The number of units exhibited by the scaler's mechanical register and the number of additional counts exhibited by the scaler were recorded. The scaler and the timer which recorded the "on" time of the scaler were reset. An initial value of the internal field counting rate could be calculated from this observation.

2. Observation of the dark decay

The internal field decay, begun at the time of transition, continued in the dark. The progress of this decay was followed by observation of the internal field counting rate as a function of time. As noted previously (Section I-C), the gamma rays required for the counting rate determination
enhance the decay of the internal field. The gamma-ray-induced decay would completely mask the dark decay if the gamma rays were allowed to be incident continuously. Therefore, the internal field was probed at intervals by observation of the counting rate for a short time. The criterion for the frequency of probing was that the amount of decay induced by the gamma rays be negligible with respect to the amount of decay which occurred between probes. The following procedure constituted a probe of the internal field. The gamma source was lowered to its counting position just before the scaler was started. The pulses produced by the diamond were counted by the scaler for thirty seconds. At the end of thirty seconds the scaler was stopped. The gamma source was then returned to its shielded position as soon as possible. After the units and additional counts were recorded, the scaler and the timer which exhibited the "on" time of the scaler were reset. The time at which the probing procedure was initiated was also recorded. This time, measured by the minute timer, was the elapsed time from the start of the internal field decay portion of the run. The internal field was probed by this procedure sufficiently often that the shape of the decay could be determined. The intervals between probings were short (two to five minutes) for the first 15 minutes, so that a moderately fast initial decay would be observed. Thereafter, intervals of 20 minutes or longer were sufficient. The dark decay was usually observed
for about one hour, but in several runs the observation time was longer. Between successive probings of the internal field, the background counting rate (due mainly to noise pulses) was observed. The scaler was activated while the gamma source was shielded to accomplish the observation. By the end of the dark decay period, the internal field had decayed from its initial value by an amount which depended on the individual diamond. In no case was the counting rate at the end of the dark decay period less than half of the initial internal field counting rate.

3. Observation of the photon-induced decay

The decay of the internal field when monochromatic light of known wavelength and intensity was incident on the diamond was the major observation of the present investigation. The rates of the decays for different wavelengths (i.e. photon energies), when referred to a common photon flux density, were expected to be greatest for the photon energies corresponding to the liberation energies of trapped charge carriers. In addition to the measurement of the internal field counting rate at various times during the photon-induced decay, a measurement of the light intensity and knowledge of the wavelength of the monochromatic light were required.

The photon-induced decay was started within a few minutes of the time of the last probe of the internal field during the dark decay portion. About ten minutes previous
to the start of the photon-induced decay, the primary light source for the monochromator was turned on so that the source would stabilize and the total intensity of the light would be steady in time. A shutter at the entrance to the monochromator prevented the light beam from reaching the diamond. During this warmup period, the wavelength to be used in the photon-induced decay portion was set on the monochromator's wavelength drum. The slit widths were adjusted to their correct settings during this same period. The settings were different for the two different primary sources. When the mercury arc source was used as the primary source the intensity of the light was adjusted by variation of the slit widths. The approximate intensity to be used could be obtained by adjustment of the slit widths to the corresponding value obtained from a calibration graph of photocell current versus slit width. These calibration curves for each wavelength used in the experiment were plotted before the experiment was started. The slit widths used with the mercury arc source corresponded to bandwidths of 10 to 50 angstroms passed by the monochromator. When the incandescent source was used, the slit widths were kept constant for any one wavelength, although they were changed for the different wavelengths. The intensity was adjusted by variation of the power to the lamp. The values of slit widths used with the incandescent source were compromises between widths sufficiently wide to provide a high intensity output
beam and sufficiently small to provide a precise value of the wavelength which caused the decay. The slit widths used with the incandescent source corresponded to bandwidths of about 40 angstroms for the visible and ultraviolet wavelengths and about 500 angstroms for the near infrared wavelengths.

About one minute before the photon-induced decay portion was to be initiated, the mirror was set to direct the monochromatic beam to the photocell, and the monochromator was unshuttered. Final adjustments of the intensity of the beam were made as the photocell current was observed. When the mercury arc source was used, the wavelength drum on the monochromator was rotated slightly to obtain the maximum photocell current. The maximum photocell current was obtained when the peak of the discrete spectral line was being passed by the monochromator. When the final adjustments were completed, several observations of the photocell current were recorded. These observations allowed the intensity of the light to be determined. The monochromator was again shuttered, and the mirror was rotated to its diamond illumination position. The preparations for the photon-induced decay portion of the run were then complete. To initiate this final portion of the run, the shutter was removed from the monochromator entrance port, causing the monochromatic beam to illuminate the diamond. The internal field in the diamond immediately began to decay more rapidly than it had just before the light was applied to the diamond. To follow the decay while not adding
significantly to it, the thirty second counting procedure for probing the internal field was used during this portion also. This procedure was described in the previous section. The rapidity of the decay dictated the intervals between successive probings. The first probe was usually made one minute after the light was applied to the diamond. The probes were continued until the counting rate obtained during the thirty second probe was insignificantly low (a few counts greater than the background). When this point was reached, the mirror was rotated back to its photocell illumination position, so that another set of determinations of the photocell current could be made. This set of determinations served as a check on the variation of the light intensity during the photon-induced decay portion. Variations were usually very small (about the size of the reading error of the microammeter), so the average of all determinations (before and after) was used as the best estimate of the photocell current in the determination of the light intensity.

D. Restoration to the Initial State

The purpose of this procedure was to restore the diamond to the same condition for the start of each successive run. This restoration is required in order that the results of the different runs with different wavelengths and intensities might be compared. One possible method to accomplish the
restoration would be to cause the complete decay of the internal field. This complete decay was the goal of each of the procedures to be described. The low counting rate which signalled the end of the observation of data did not necessarily signify that the internal field had decayed completely. The procedures attempted were supposed to accomplish this complete decay.

For the runs taken in Apparatus II, the diamond was left in the dark with the electrodes at ground potential for at least six hours before starting another run. Any remaining internal field decayed in the dark during this period. For the runs taken in Apparatus I, the diamond was subjected to the gamma radiation for about one hour after the photon-induced decay portion. The diamond was grounded during this bombardment period and for the remainder of the time until the next run was initiated. The total time of this restoration period was about 18 hours. The criterion for the success of the restoration procedure was taken to be the consistency of the shape of the applied field counting rate variations with time. No significant difference in the reproducibility of the applied field counting rate variation with time was observed with the two procedures already described, or with several other attempted procedures. These other procedures employed light of various wavelengths and bands of wavelengths in the place of gamma rays in the restoration procedure described for Apparatus I.
The restoration of the diamond to a consistent initial state for each run appeared to be rather independent of the procedure used. Variations in the results of the experiment exhibited no apparent correlation with changes in the restoration procedure. The initial state of the diamond need not be identical for the results of the runs to be comparable, it appears. The critical state is more likely the state of the diamond at the start of the internal field decay portion of the run. This state may be governed more by the applied field counting portion than the restoration period.
IV. EXPERIMENTAL DATA

A. Description of the Diamonds

This experiment has been performed on two diamonds from the collection of counting diamonds owned by the Ames Laboratory. These two were chosen because they are the best counters under internal field conditions. In addition, some optical and electrical properties of these specimen had been investigated by previous workers. Diamond One (henceforth abbreviated D1) was a clear, colorless crystal with approximately rectangular faces of 4.7 by 4.3 millimeters. These faces were plane except for two faults: a V-shaped cavity occurred in one face, and a small irregular piece jutted above the other face at one corner. There were no other obvious flaws. The diamond was slightly wedge shaped over its thickness, varying from 0.3 millimeter at one corner of the face to 0.6 millimeter at the diagonally opposite corner. The other specimen, Diamond Four (henceforth abbreviated D4), was also clear and colorless. This diamond had faces of equilateral triangular shape, about 3.5 millimeters on a side. The faces were quite flat and were 0.7 millimeter apart. There were no obvious flaws in this diamond.

B. Applied Field Counting Rate Data

The data obtained from the applied field counting portion of each run was the counting rate, $R_a$, as a function of
the elapsed time of the run. These data were obtained mainly as a check on the reproducibility, from run to run, of the magnitude of the internal field created during this portion. The counting rates were obtained from the five-minute totals printed on the automatic read-out tape by division of each of these totals by 5. A graph of $R_a$ versus the elapsed time was plotted for each run. The shape of this graph was roughly constant for the set of runs on each diamond in each apparatus. Because the shapes of the curves for different runs were all similar, and because fluctuations of individual runs were not apparently correlated with fluctuations in the final experimental results, the variation of the average counting rate, $\bar{R}_a$, with time will be displayed for each diamond in the succeeding paragraphs. The $R_a$ from individual runs at common times were averaged to obtain $\bar{R}_a$ for that time.

1. **Diamond One**

The 86 runs on D1 can be logically divided into two parts: 60 runs in Apparatus I, and 26 runs in Apparatus II. Figure 10 shows the variation of $\bar{R}_a$ with time for runs in Apparatus I. A smooth curve has been drawn through the data. The standard deviation of the individual runs from the average is represented by the two dotted curves. This deviation represents the effect of large fluctuations in the counting rates for the first third of the total number of runs used in this average. The fluctuations in the rest of the runs
were smaller by a factor of 2 or 3. This diamond had an initial $\bar{R}_a$ of 118 units per minute. The counting rate dropped gradually with time as the internal field built up. At the end of an hour $\bar{R}_a$ was about one-half of its initial value and was changing only slowly with time. Figure 11 is the corresponding curve for the same diamond in Apparatus II. The shape of this curve is quite different from that obtained in Apparatus I. The Apparatus II curve (Figure 11) decreases initially more rapidly than the Apparatus I curve (Figure 10). The rapid decrease soon changes to a very slow decrease that continues for the remainder of the hour counting period. The difference in shape of the curves from the different apparatus is correlated with a difference in the internal field decay data in the two cases. The correlation will be pointed out later in this section. The cause of this change in shape is not known. It is interesting to note that the $\bar{R}_a$ versus time curves of some preliminary data on D1 in Apparatus II had shapes quite similar to that shown in Figure 10. The preliminary data was taken to check Apparatus II and is not further reported in this thesis. The fact that the Apparatus I curve and the curves from the preliminary runs in Apparatus II are similar suggests that the change was in the diamond rather than in the apparatus.

2. **Diamond Four**

All of the data on D4 were taken in Apparatus II. The
Figure 10. Average variation of applied field counting rate with time for D1 in Apparatus I.
Figure 11. Variation of applied field counting rate with time for D1 in App. II.
variation of $\bar{R}_a$ with time is shown in Figure 12. The standard deviation of the individual runs from the average value is represented by the dotted lines. This diamond exhibited only a small decrease in $\bar{R}_a$ with time over the entire hour counting period. However, an appreciable internal field counting rate was obtained in the subsequent internal field decay of each run. Since the decrease in the effective electric field, $E_\text{e}$, in the diamond during the applied field portion is assumed to be equal to the increase in the internal field, $E_\text{i}$, generated by the trapped charges (see Equation 13, Section I-B-2) the above results seem to be contradictory. This apparent discrepancy is at least qualitatively resolved by the relationship of the counting rate to the electric field in the diamond. The subject is discussed in more detail in Appendix F.

C. Internal Field Counting Rate Data

The internal field counting rate data comprise the major effort of this research. One hundred and twenty-three runs were obtained on the two diamonds in this effort. Each complete run, which included the creation and decay of the internal field as well as the restoration procedure, required at least eight hours, so a maximum of two runs were taken in one day. More often, especially in the early work, only one run was taken in a day. The procedure described in Section II-C was employed to obtain values of counting rates at various
Figure 12. Variation of applied field counting rate with time for D4 in App. II.
times during the internal field decay. The values of the internal field counting rate, $R_1$, were plotted versus their time of observation on semilogarithmic graph paper because an exponential decay was expected. This expectation was based on the following qualitative reasoning. The internal field, which is measured by the counting rate, is generated by the trapped electrons and holes. The decay of the field is presumed due to the liberation of these trapped charges. The rate of liberation is likely to be directly proportional to the number trapped at any time. So the rate of change of the number of trapped charges is proportional to the number of trapped charges. This is just the condition necessary for an exponential decay.

It is impossible to present all of the data in detail in this thesis. However, a graphical representation of the photon-induced decay portions of many runs and a tabular synopsis of all runs is presented in Appendix B. In this section some sample runs will be discussed. Run-to-run fluctuations occurred in both the shape of the decay curves and the values of $R_1$ at corresponding times. The decay curves ($\ln R_1$ versus time) from the runs on each diamond are, however, sufficiently similar in shape that a sample run can be discussed with some assurance that the qualitative features of all runs will be described. For each diamond, a sample run will be discussed in the following paragraphs. The effect of intensity on the photon-induced decay at one wavelength
will also be presented.

1. **Diamond One**

The data on Diamond One (D1) were taken in two different apparatus. The code used in the identification of the runs provides a means of separation of the runs from the different apparatus. The first number in the code was the number of the diamond, number one in this case. This number was followed by a dash and another number. This second number was the number of runs which had been taken on that diamond up to and including the run in question. For example, the thirty-seventh run on D1 was designated 1-37. The runs taken in Apparatus I had numbers less than 85 for their second number. For Apparatus II runs the second numbers were greater than 100. (The coding system was started at 100 for these latter runs.)

a. **Shape of the internal field counting rate decay curve**

Figure 15 is a semilogarithmic graph of the data taken from a sample run in Apparatus I. The $R_1$'s observed by the probing procedure described in III-C have been plotted on a logarithmic scale versus the time at which the probes were made.

Several aspects of this graph should be noted. The initial $R_1$ of 100 units per minute is greater than the final $R_a$ shown in Figure 10. The total decay time is of the order of two hours, so long term effects are being studied. The standard error, $\delta R_1$, assigned to each $R_1$ determination was obtained from the usual formula for counting rate errors,
Figure 13. A sample of the internal field counting rate decay observed with D1 in Apparatus I.
\[ \delta R_1 = \left( \frac{R_1}{t} \right)^{1/3} \]  

where \( t \) is the time of observation of \( R_1 \), in this case one-half minute. Three regions of the decay curve are clearly shown in the figure. The first two regions, Region I and Region II on the graph, occur with the diamond in the dark. The procedure for the observations was described in Section III-C-1 and Section III-C-2. The final region, Region III in the figure, displays the data from the photon-induced decay portion of the experiment. A fast initial decay (Region I) which occurs within the first ten minutes of the decay period, is exhibited by this diamond. This fast initial decay could be an exponential decay superimposed on the slow dark decay shown in Region II. The slow dark decay (Region II) appears to be an approximate exponential decay which can be characterized by a small decay constant. This decay constant is equal to the absolute value of the slope of the straight line passing through the datum points. The decay in Region III exhibits some curvature in this semilogarithmic plot. Although this particular sample curve does not straighten out at the low counting rates, the curves in Region III usually approached a straight line for the lower counting rates. The Region III plots of other runs from Apparatus I are displayed in Appendix B.

Figure 14 is the semilogarithmic plot of the decay of \( R_1 \) from a sample run on D1 in Apparatus II. The same three
Figure 14. A sample of the internal field counting rate decay observed with DI in Apparatus II.
regions of the curve are noted in this run as were noted in Figure 13. However, several differences between the curves can be noticed. The counting rate level is lower for this run than for the run from Apparatus I: i.e., the $R_1$'s observed in Regions I and II are smaller in Figure 14 than in Figure 13. This difference can be resolved by considerations of gamma source strength decay and geometrical factors. These considerations will not be discussed here. The fast initial decay in Region I is faster for the runs from Apparatus II (represented by Figure 14) than for those from Apparatus I (represented by Figure 13). The slow dark decay is hardly perceptible in the run from Apparatus II, while a comparatively fast decay is observed in the same region for the run from Apparatus I. The difference in the shapes in Regions I and II for the runs from the different apparatus is correlated with the shape change in the $R_\alpha$ versus time curves from the different apparatus. A comparison of Figures 10, 11, 13 and 14 will illustrate the correlation. Further investigation is required before this difference can be explained.

b. Effect of light intensity on the photon-induced decay

The dark decay, in Regions I and II, of all the runs taken in one apparatus varied only slightly from run to run. However, the photon-induced decay in Region III varied radically with both wavelength and intensity. Each run was taken with a different set of light conditions than its predecessor. The runs were purposely not taken in order of increasing or
decreasing wavelength. On the contrary, the selection of wavelengths employed in successive runs was quite random, so that cumulative effects would not disturb the results. The selection of wavelengths was restricted for any one run because two different photocells which were sensitive to different parts of the spectrum were used in the intensity measurement. These photocells were not easily changed so the runs were taken in groups, each group taken with wavelengths to which the photocell in use was sensitive.

Region III plots, the P I D portions of three runs from Apparatus II are shown in Figure 15. These runs were taken with different intensities of the same wavelength (546 milli-microns). The relative intensities, I, used in these runs are noted on the figure. The start of the photon-induced decay of each run is denoted by the vertical dotted line. A straight line has been drawn through the lower counting rate data for each run. The counting rates in the range from 1 to 10 units per minute were given more weight in the determination of this line than were the other counting rates. The extra weight was given to the middle decade because the larger $R_i$'s deviated systematically from the straight line, and the smaller $R_i$'s were so small that they tended to scatter radically. The line is curved at the upper end to match the dark decay data. The shape of the decay is quite independent of the intensity, but the rate of the decay varies radically with intensity.
Figure 15. The effect of different intensities of 546 millimicron light on the photon-induced decay in Apparatus I.
2. Diamond Four

The decay of $R_1$ from a sample run on D4 is shown in the semilogarithmic plot given as Figure 16. The code used to identify runs was the same one used for D1. Run 4-31 signified that this was the thirty-first run on D4. No fast initial decay is observed with this diamond so there is no Region I on this graph. Also, the dark decay is negligible over the period of three hours as shown in the figure. The photon-induced decay (Region III) exhibits the same shape that the D1 runs did. Again the decay appears to be exponential for the lower counting rates.

The effect of light intensity on the photon-induced decay is shown in Figure 17. The common wavelength in this case was 404 millimicrons. Relative intensities are again noted on the figure. The same comments made for Figure 15 apply to Figure 17.
Figure 16. A sample of the internal field counting rate decay observed with D4 in Apparatus II.
Figure 17. The effect of different intensities of 404 millimicron light on the photon-induced decay in D4 in Apparatus II.
V. DATA ANALYSIS AND RESULTS

The data, presented in brief in the preceding section and more completely in Appendix B, show the variation of the internal field counting rate, $R_i$, with time. In order to obtain some meaningful numbers from these data, one would like to convert the $R_i$ value to a value of internal field, $E_i$, because $E_i$ is more directly related to the number of trapped charges. This conversion may be accomplished by two methods. One method is a conversion by the assumption that $R_i$ varies linearly with $E_i$ for small fields. The other method is the conversion by means of an experimentally determined graph of the counting rate as a function of the electric field. Since this latter procedure is the more logical, the analysis based on this conversion will be presented first. The other method will be discussed, and the results from the two methods will be compared in the final parts of this section.

A. Conversion of Counting Rate to Internal Field

The conversion of $R_i$ to $E_i$ through an experimentally determined graph of counting rate as a function of electric field is based on the assumption that $R_i$ is the same function of the electric field that the applied field counting rate, $R_a$, is. The validity of this assumption will be discussed in a later section. The conversion curve is obtained simply from a measurement of $R_a$ for various values of applied
voltage. The details of this auxiliary experiment performed on both diamonds are given in Appendix C. The conversion curves are given as Figures 54 and 55 in this appendix.

1. **Mechanics of the conversion**

   With the aid of the experimental curves, the conversion was straightforward. The intersection of the observed value of $R_1$ with the conversion curve was at the value of $E_1$. The standard error, $\delta R_1$, of $R_1$ was converted in the following manner. The conversion curve, being experimental, has an error associated with it. Two more curves were drawn (one on each side of the standard curve) which represented the boundaries of the region of the plot in which there was about a 70 percent chance that the true curve lay. The upper limit of the counting rate ($R_1 + \delta R_1$) was transformed with the lowest curve, and the lower limit of the counting rate ($R_1 - \delta R_1$) was transformed with the highest curve.

2. **Examples of the conversion**

   The conversion of the data for D1 and D4 taken in Apparatus II was accomplished by the method described above. A conversion curve was not obtained for the data taken in Apparatus I. Unfortunately, space limitations will not allow the display of all the converted data. Examples of the converted data for some runs will be given. These examples will suffice to show the general features of the decay of the internal field. Only the photon-induced decays will be shown
since they are the major concern of the experiment. The conversion does not significantly change the dark decay data.

a. **Diamond One** The converted data for the runs shown in Figure 15 in the preceding section (IV) are given in Figure 18. The internal field appears to vary exponentially with time initially but then tails off, decaying more slowly in time than the exponential variation demands. This appears to be a general result for all runs. The effect of intensity is not appreciably affected by the transformation.

b. **Diamond Four** The converted data for the runs shown in Figure 17 of Section IV are given in Figure 19. The decay of E1 in this diamond was exponential over a wider range than that in D1. Again the intensity effect is unchanged by the conversion.

**B. Specification of Decay Constants**

The photon-induced decay data obtained for both diamonds vary with both wavelength and intensity of the incident light. The numerical description of these two variations is dependent on the enumeration of a quantity characteristic of the decay. In the case of an exponential decay the logical choice is the decay constant. The important portion of the decay was assumed to be the initial exponential portion. This assumption is based on the fact that both the original counting rate data and the converted data are more reliable
Figure 18. Converted photon-induced decay data for D1 in Apparatus II.
Figure 19. Converted photon-induced decay data for D4 in Apparatus II.
at the larger values. The slope of the straight portion on the semilogarithmic plot of this exponential decay was determined for each run. The absolute value of this slope is the decay constant, $b_p$. The decay constants for the majority of the runs were caused to be of the same order of magnitude by the purposeful adjustment of the intensity of the illumination. With decay constants of this order of magnitude the photon-induced decay was rather rapid (5 to 50 minutes) on the time scale of a total run. This rapid decay meant that corrections for the slow dark decay (Region II, Figures 13, 14, and 16) during the photon-induced decay (Region III) were negligible and further, that two complete runs were often possible in a day.

C. Effect of Light Intensity

The decay constant, $b_p$, varies with the intensity of the light, i.e., with the photon flux density, $\phi$, at a particular wavelength. This photon flux density was measured by the photoelectric cell. Determination of the form of the variation requires a knowledge of the relation between the measured photocell current, $J$, and $\phi$ at the diamond. The basic relation for an idealized situation will be developed first. The actual situation and necessary corrections will then be discussed, followed by the display of the variation of $b_p$ with $\phi$. 
1. **Idealized situation**

The idealized situation is that in which the monochromatic light beam, incident on the photocell, is equally intense over its entire beam area. Then $J$ is a direct measure of $\phi$. For purposes of determining the variation of $b_p$ with $\phi$, $b_p$ can be plotted versus $J$ under these conditions. If the actual intensity of the light is required, a knowledge of the sensitivity of the photocell is demanded.

2. **Actual situation**

The actual situation was different from the idealized situation as a result of the variation of the intensity over the area of the monochromatic beam. An auxiliary experiment, described in Appendix D, had to be performed to obtain the correct relation of the $\phi$ to $J$. The conversion numbers obtained from this auxiliary experiment are given in Tables 11 and 12 in Appendix D. The observed photocell currents were multiplied by these conversion numbers to obtain the corrected values.

3. **Intensity effect - Diamond One**

A plot of $b_p$ versus $\phi$ at a wavelength of 435 millimicrons for D1 is shown in Figure 20. The intensity effect plots at the other wavelengths are given in Appendix E. The error bars are the standard errors assigned to $b_p$ in a manner described in Section VII. The data scatter considerably, but $b_p$ tends to increase with increasing $\phi$. The exact relation
Figure 20. Intensity effect plot for 435 millimicron light on D1 in Apparatus II.
of \( b_p \) and \( \phi \) is difficult to establish experimentally. The decay constant was taken to vary linearly with \( \phi \) because the majority of the data seem to demonstrate rough linearity and because a linear relationship is expected from the theoretical interpretation to be given. The origin was considered to be an experimental point because the decay constant describing the slow dark decay \((\phi = 0)\) was negligibly small for D1 in Apparatus II. (See Figure 14, Region II) The best (in the author's judgement) straight line passing through the origin and fitting the other experimental points was drawn for each of the intensity effect plots. The slope of the straight line was assumed to be the rate of variation of \( b_p \) with \( \phi \).

As a check on the experiment, a photon-induced decay was observed at 435 millimicrons with the incandescent source as a primary light source instead of the mercury arc source. This point is denoted by the square in Figure 20.

4. **Intensity effect - Diamond Four**

The intensity effect plot for 404 millimicron light on D4 is given as Figure 21. The plots at the other wavelengths are given in Appendix E. The same comments given for Figure 20 apply to Figure 21. The scatter was generally smaller for the D4 data. The two incandescent lamp check points are denoted by squares.
Figure 21. Intensity effect plot for 404 millimicron light on D4 in Apparatus II.
D. Effect of Photon Energy on Internal Field Decay

The exhibition of the effect of photon energy, \( W \), on the decay of the internal field was the ultimate aim of this experiment. It was anticipated that this exhibition would display the energy levels of traps in the photon energy region studied. The most logical method for the extraction of these results is to plot, versus \( W \), the \( b_p \)'s corresponding to a constant \( \phi \) incident at all \( W \). Each of these special \( b_p \)'s will be denoted by \( B \). Since the ranges of \( \phi \) differed for the intensity effect plots at the various photon energies, use had to be made of the linear dependence of \( b_p \) on \( \phi \). The special photon-induced decay constant at each photon energy was determined by the formula,

\[
B = \left( \frac{\Delta b_p}{\Delta \phi} \right) \phi_c
\]

where \( \left( \frac{\Delta b_p}{\Delta \phi} \right) \) is the slope of the intensity effect plot and \( \phi_c \) is the photon flux density common to all \( W \)'s. The results of this determination are shown in Figures 22 and 23. The logarithm of \( B \) has been plotted versus \( W \) for each diamond. Semilogarithmic plots were required to show the total variation of \( B \). The common photon flux density for these plots for both diamonds was \( 10^{16} \) photons cm\(^{-2} \) sec\(^{-1} \). The photon energies used in the experiment corresponded to wavelengths scattered throughout the entire visible light region and on into the near infrared and near ultraviolet regions. The two
Figure 22. The variation of the photon-induced decay constant with photon energy for DI in Apparatus II.
Figure 25. The variation of the photon-induced decay constant with photon energy for D4 in Apparatus II.
diamonds appear to exhibit very similar dependences of $B$ on $W$. However, the absolute values of $B$ are different in the two cases. The most rapid variation of $B$ is in the energy range from 1.9 to 2.3 ev. The decay constant continues to rise as $W$ increases, but the variation is more gradual. The decay constant for D1 exhibits a monotonic increase throughout the photon energy range studied, but $B$ for D4 appears to reach a maximum around 3.3 ev. If these same data were plotted on a linear graph, the only noticeable variation of $B$ would be in the region of $W$ above 2.4 ev. A linear graph of this type will be given in Section VI.

E. An Alternate Analysis

This analysis is based on the expectation that the internal field counting rate, $R_i$, will vary linearly with the internal electric field, $E_i$, for small values of the field. The pulse height variation with small applied fields is expected on theoretical grounds to be linear (see Section I-B-1). If $R_i$ is taken to be a measure of an average pulse height then $R_i$ also would vary linearly with $E_i$. If $E_i$ decays exponentially, then one would expect $R_i$ to decay exponentially for small values of $R_i$. This expectation is realized, as a consideration of the data in Section IV and Appendix B will confirm.
1. Application and results - Apparatus II

The decay constant, $b'_p$, of the exponential portion of each of the runs for D1 and D4 was determined from the slope of the straight section of the semilogarithmic plot. Intensity effect plots for each wavelength were drawn in the same manner as in the first analysis. The effect of photon energy on the decay was also determined as above. The special photon-induced decay constant is denoted as $B'$ for this alternate analysis. A comparison of the results of the two analyses is presented in Table 1 for D1 and Table 2 for D4. For D4 the results of the two methods agree rather well, while for D1 there is a discrepancy. However, this discrepancy is not large with respect to the total variation of the decay constant over the complete range of $W$.

Table 1. Comparison of results from the two analyses for D1 in Apparatus II

<table>
<thead>
<tr>
<th>Photon energy, W (ev)</th>
<th>Photon-induced decay constant, $B'$, from second analysis (sec)^{-1}</th>
<th>Photon-induced decay constant, $B$, from first analysis (sec)^{-1}</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.65</td>
<td>1.0 ± 0.5 x 10^{-2}</td>
<td>9.0 2.5 x 10^{-3}</td>
</tr>
<tr>
<td>1.85</td>
<td>2.6 0.4 x 10^{-2}</td>
<td>1.59 0.22 x 10^{-2}</td>
</tr>
<tr>
<td>1.97</td>
<td>5.1 1.5 x 10^{-2}</td>
<td>4.7 1.0 x 10^{-2}</td>
</tr>
<tr>
<td>2.15</td>
<td>1.59 0.33</td>
<td>9.0 1.6 x 10^{-1}</td>
</tr>
<tr>
<td>2.27</td>
<td>5.5 2.5</td>
<td>2.9 1.0</td>
</tr>
<tr>
<td>2.75</td>
<td>4.9 0.5 x 10^{1}</td>
<td>3.47 0.40 x 10^{1}</td>
</tr>
<tr>
<td>2.85</td>
<td>8.4 1.0 x 10^{1}</td>
<td>4.7 0.8 x 10^{1}</td>
</tr>
<tr>
<td>3.07</td>
<td>1.34 0.22 x 10^{2}</td>
<td>8.8 1.4 x 10^{1}</td>
</tr>
<tr>
<td>3.40</td>
<td>2.37 0.22 x 10^{2}</td>
<td>1.53 0.17 x 10^{2}</td>
</tr>
<tr>
<td>3.54</td>
<td>3.8 0.5 x 10^{2}</td>
<td>2.3 0.6 x 10^{2}</td>
</tr>
</tbody>
</table>
### Table 2. Comparison of results from the two analyses for D4 in Apparatus II

<table>
<thead>
<tr>
<th>Photon energy, W (eV)</th>
<th>Photon-induced decay constant, $B'_{\text{from second analysis}}$ (sec$^{-1}$)</th>
<th>Photon-induced decay constant, $B'_{\text{from first analysis}}$ (sec$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.85</td>
<td>$2.67 \pm 0.29 \times 10^{-3}$</td>
<td>$2.4 \pm 0.4 \times 10^{-3}$</td>
</tr>
<tr>
<td>1.97</td>
<td>$6.4 \pm 0.6 \times 10^{-3}$</td>
<td>$5.71 \pm 0.48 \times 10^{-3}$</td>
</tr>
<tr>
<td>2.15</td>
<td>$7.7 \pm 1.8 \times 10^{-2}$</td>
<td>$9.0 \pm 1.5 \times 10^{-2}$</td>
</tr>
<tr>
<td>2.27</td>
<td>$2.5 \pm 0.5 \times 10^{-1}$</td>
<td>$2.4 \pm 0.8 \times 10^{-1}$</td>
</tr>
<tr>
<td>2.85</td>
<td>$1.84 \pm 0.23 \times 10^{1}$</td>
<td>$2.08 \pm 0.26 \times 10^{1}$</td>
</tr>
<tr>
<td>3.07</td>
<td>$3.67 \pm 0.40 \times 10^{1}$</td>
<td>$4.41 \pm 0.43 \times 10^{1}$</td>
</tr>
<tr>
<td>3.40</td>
<td>$1.16 \pm 0.09 \times 10^{2}$</td>
<td>$1.18 \pm 0.12 \times 10^{2}$</td>
</tr>
<tr>
<td>3.54</td>
<td>$7.5 \pm 0.7 \times 10^{1}$</td>
<td>$9.1 \pm 1.6 \times 10^{1}$</td>
</tr>
</tbody>
</table>

2. **Application and results - Apparatus I**

It seems reasonable on the basis of the agreement above to consider the analysis of the data on D1 taken in Apparatus I. These data can be analyzed only by this alternate method. The photon-induced decay constants for this analysis are listed in Table 4 in Appendix B. The intensity effect graphs had to be plotted with $J$ as the abscissa because $\varphi$ was not determined in an auxiliary experiment in this apparatus. These plots showed an upward curvature not observed in those given in Appendix E. The photon flux density was determined from the photocell current in the manner suggested for the idealized case discussed in Appendix D. The dependence of $B'$ on $W$ at the same $\varphi_c$ used in the plots for D1 and D4 in the previous analysis is shown in Figure 24. For comparison,
Figure 24. Comparison of the effect of photon energy on the photon-induced decay constant for DI in two apparatus.


diamond one (DI) in apparatus I

triangle diamond one (DI) in apparatus II

common photon flux density

$= 10^{16}$ photons cm$^{-2}$ sec$^{-1}$
the corresponding results for D1 in Apparatus II are plotted on the same graph. The dependence on W is roughly similar, but the absolute values are an order of magnitude different. This large discrepancy might be resolved if the actual intensity of the light striking the diamond were known.
VI. INTERPRETATION

In the Introduction to this thesis, the proposed experiment was discussed. In that discussion the basis of a qualitative interpretation of the effect of light on the internal field in a diamond was presented. The internal field was assumed to decay because photons liberated the trapped charges generating the internal field. This assumption is developed in detail, both qualitatively and quantitatively, in the first part of this section as the first interpretation. This interpretation is not the only one capable of explaining the results, however. In the last part of this section a different and perhaps more realistic interpretation will be presented. This second interpretation assumes that the trapped charges are neutralized rather than liberated. The neutralization process is photoconduction. Each model will be discussed in the light of evidence available from auxiliary experiments and published material. Both of the interpretations to be presented are based on the assumption that the counting rate observed in the absence of an applied electric field is a result of a persistent internal electric field generated by the trapped charges in the diamond. This assumption is consistent with the results of this experiment.

A. The First Interpretation: Detrapping Model

1. **Qualitative Interpretation**

   The internal field at any point in the diamond at any
time is dependent in general on both the amount and distribution of the trapped charges throughout the diamond. A change in the internal field can be caused by a change in the amount of trapped charge, and/or a change in distribution of this charge. With either possibility in this interpretation, the trapped charge must be liberated before any change can occur. This is an important point, because then the qualitative interpretation of the results is reduced to the elucidation of the mechanism of liberation. Further consideration will have to be given to the different causes of decay of the internal field before a quantitative interpretation can be developed in a later part of this section.

a. **Mechanism for the dark decay** The internal field decay in Regions I and II (Figures 13, 14 and 16) occurs in the dark. The mechanism for the liberation of the trapped charges in this case is assumed to be excitation by thermal agitation. With this liberation mechanism, the more shallow the trap (i.e., the smaller the difference in energy of the charge carrier in its bound state and its energy in the band in which it is mobile), the faster the trap is emptied. The decay in Region I is assumed to be caused by liberation from a different level than the decay in Region II. The fast initial decay corresponds to liberation of shallow traps, while the slow thermal decay corresponds to liberation from a deeper level of traps. The fact that only the slow thermal decay is observed with D4 is a manifestation of the absence
of the shallow level which occurs in D1. In both diamonds, there may be still shallower levels which are emptied in times of the order of the time for transition from applied field to internal field counting. For instance, McKay (32) has observed an internal field decay occurring in microseconds. He ascribed this decay to the liberation of traps with a thermal liberation energy of about 0.3 electron volt.

b. Mechanism for the photon-induced decay

The photon-induced decay (Region III, Figures 13, 14 and 16) is, as its name implies, caused by the excitation of charge carriers by photons. The charge carriers must be introduced into the band in which they are mobile in this process. The results embodied in Figures 22 and 23 in Section V show that there is a wide variation of liberation ability in the range of photon energies studied. Photons with energies greater than 3 ev appear to have the maximum effectiveness in this range. From these results one would expect a deep trapping level to exist in about the middle of the forbidden gap.

2. Band model and decay mechanisms

The qualitative interpretation can be used to formulate an energy level scheme for some of the trapping centers in diamond. This energy level scheme can then be used to display the mechanisms for the dark decays and photon-induced decays.

a. Energy level scheme

The qualitative interpreta-
tion leads to the expectation of both shallow and deep traps in diamond. The data do not, however, give an indication of which of these act as electron traps and which as hole traps, nor does this information appear to be derivable from published data. The arbitrary assignment of the deep traps as hole traps and the shallow traps as both hole and electron traps will be made here. However, permutations of these assignments can be used to explain the decay. It should be noted that both electrons and holes must be trapped to cause a persistent internal field. If either sign of charge were not trapped, then when the applied field was removed, that charge would rapidly flow to and neutralize the charge of opposite sign.

The energy band scheme which has been assumed for this interpretation is shown in Part A of Figure 25. This is the band picture of the diamond before an electric field is applied and before counting is begun. In diamond, the valence band is normally full of electrons and the conduction band is normally empty. The discrete energy states in the energy gap between these bands are the levels due to trapping centers. The normally empty discrete level closest to the conduction band will act as a trap for electrons while the lower two normally filled levels will act as hole traps. The band gap energy is roughly 5.4 ev. The energies assigned to the levels close to the band edges are those expected from published values of shallow trap depths 0.5 ev and 0.7 ev (30).
Figure 25. Energy level schemes for detrappling model.
In order to make the subsequent arguments more specific, a value of 3.0 ev will be assigned to the level in the middle of the band gap. This level is responsible for the photon-induced decay results (Figures 22, 23 and 24). Its value is certainly not pinpointed by these results, but the value is in this range. For simplicity, only one energy level near the center of the band gap has been assumed in this scheme. 

b. Explanation of the decay  Part B of Figure 25 shows the band picture at the start of an internal field decay run. The portion of the diamond near the left hand electrode (which was the anode during the applied field part of the run) has an excess of electrons over its normal population and therefore is negatively charged. The portion near the right hand electrode is positively charged having trapped holes. The internal electric field is directed from right to left. 

The various portions of the internal field decay (shown as the different regions of the graphs given as Figures 13, 14 and 16 in Section IV) can be interpreted with the aid of Figure 26. Each part of the figure displays the mechanism for a particular portion of the decay. The decay proceeds in time in the natural order: Part A first, then Part B and finally Part C. This is the order in which the experimental data were taken. Each energy level which has trapped a charge carrier is noted in the figure by a circle enclosing the sign of the trapped charge at that site. The circles
PART A. FAST INITIAL DECAY MECHANISM

PART B. SLOW DARK DECAY MECHANISM

PART C. PHOTON-INDUCED DECAY MECHANISM

Figure 26. Mechanisms for decay: detrapping model.
are positioned above the levels.

The mechanism for the fast initial decay is shown in Part A of Figure 26. This decay is shown as Region I of Figures 13 and 14. An electron is thermally excited (a) from the valence band to the trapping level, leaving a hole in the valence band. This hole moves (b) across the diamond to the vicinity of a trapped electron. The trapped electron, preferring to reside in its lowest energy state, drops (c) into the hole. (Alternately, the hole could become trapped in this negative part of the diamond.) This process continues until all of the discrete levels closest to the valence band have been filled.

The mechanism for slow decay in the dark (Region II, Figures 13, 14 and 16) is shown in Part B. For this decay, the trapped electron is thermally excited (d) to the conduction band. It drifts (e), under the influence of the internal field, to the positively charged region, in which it drops (f) into an empty level, thereby annihilating or neutralizing a trapped hole. This process continues for the remainder of the dark decay, but does not reach completion in the short time observed.

Part C shows the mechanism of the photon-induced decay (Region III). An electron in the valence band absorbs the incident photon and is excited (g) to the 3.0 ev level. The hole left in the valence band by this excitation drifts (h) to and annihilates (j) or neutralizes a trapped electron.
This process completes the decay.

3. **Quantitative interpretation**

On the basis of the model presented above, one can make a quantitative interpretation of the results.

a. **A simple theory** In the interest of simplicity, a particular distribution of trapped charge will be assumed. This distribution is a uniform distribution of both trapped holes and electrons throughout the volume. For purposes of calculation, the average internal field generated by this distribution may be considered to be a result of two oppositely charged planes of charge some distance apart. This distribution is assumed to remain constant in space throughout the decay. Then the internal field, \( E_i \), is directly proportional to the net charge on either of these planes. This charge is directly proportional to the density, \( N_t \), of trapped charges of one sign in the interior volume.

The probability per second of liberation of a given trapped charge will be denoted by \( P \). The rate of change of the number of trapped charges is

\[
\frac{dN_t}{dt} = -PN_t \tag{18}
\]

or

\[
\frac{d\ln N_t}{dt} = -P.
\]

Since \( E_i = KN_t \) where \( K \) is a constant independent of \( t \), then

\[
\frac{d\ln E_i}{dt} = -P. \tag{19}
\]
The problem of interpretation is reduced to the discovery of the probability per unit time of the liberation of a trapped charge by the different mechanisms. The decay constant, $b$, of the exponential decay is just equal to $P$.

b. **Energy levels of the shallow traps** The probability per second for the thermal liberation of a trapped charge from a level with a trapping depth $W_t$ is given by Randall and Wilkins (44) to be

$$P_1 = s \exp \left( -\frac{W_t}{kT} \right)$$

where $s$ is the so-called attempt-to-escape frequency, $T$ is the absolute temperature, and $k$ is Boltzmann's constant. $P_1$ is equal to the dark decay constant, $b_d$. The diamond remained at room temperature during the decay, so if a value of $s$ were known the thermal depth of the trap would be calculable. Bull and Garlick (17) in their work on luminescence of diamond estimated $s$ to be of the order of $10^6$ seconds$^{-1}$. The thermal depth of the shallow hole trap which is associated with the fast initial decay (Region I, Figures 13 and 14) will be estimated first. Since this decay appears to reach completion in from 5 to 15 minutes, a reasonable estimate of the decay constant would lie in the range from 1 to 1/3 min.$^{-1}$. For ease in calculation, $P_1$ will be taken as 0.01 sec$^{-1}$ for this fast initial decay. Equation 20 can be solved for $W_t$ when this value of $P_1$ is entered into the equation. At room temperature $W_t$ is calculated to be approximately 0.5 ev.
The slow decay in the dark (Region II) has a measurable decay constant only for the D1 data taken in Apparatus I. The average value of this decay constant for all the runs in the apparatus was about $10^{-5}$ sec$^{-1}$. Use of this value in Equation 20 gives a trap depth $W_t$ of about 0.6 ev for this deeper trap. These calculated trap depths are, of course, only rough values based on order of magnitude observations. They are, however, in reasonable agreement with previously reported values (29,30,41).

c. Liberation cross-sections For the case of liberation of trapped charge by photons, it is reasonable to assign a cross-section, $\Sigma$, to the process of liberation. On the assumption that only one trapping level (at approximately 3.0 ev) appears in the photon energy range investigated, the probability per second of liberation of a given charge is

$$P_2 = \Sigma \phi ;$$

or, if $b_p$ is the photon-induced decay constant,

$$b_p = \Sigma \phi$$ (21)

where $\phi$ is the photon flux density in the diamond. The cross-section, $\Sigma$, is a function of photon energy. At any one photon energy, $b_p$ is directly proportional to $\phi$. This linear relationship appears to be substantiated by the intensity effect plots (Figures 56-71, Appendix E).

If a common photon flux density, $\phi_c$, is used for all
photon energies, the corresponding $b_p$, which is called $B$ for this special case, will be

$$B = \Sigma \phi_c \text{.} \quad (22)$$

A plot of $B$ versus photon energy, $W$, will denote the variation of $\Sigma$ with $W$. This graph is just that shown in Figure 22 for D1 and Figure 23 for D4. Division of Equation 22 by $\phi_c$ yields

$$\Sigma = B / \phi_c \text{.} \quad (23)$$

Then, if $\phi_c$ is known, the cross-section may be calculated. Since $\phi_c$ for Figures 22 and 23 is $10^{16}$ cm$^{-2}$ sec$^{-1}$, the numbers on the ordinate axis of these figures can be changed to values of $\Sigma$ merely by the multiplication by $10^{-16}$ cm$^{-2}$ sec$^{-1}$.

For convenience, the cross-sections observed in this experiment are given in Table 3.

<table>
<thead>
<tr>
<th>W (ev)</th>
<th>$\Sigma$ for D1 (cm$^2$)</th>
<th>$\Sigma$ for D4 (cm$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.85</td>
<td>1.59 $\pm$ 0.20 x 10^{-18}</td>
<td>2.4 $\pm$ 0.4 x 10^{-19}</td>
</tr>
<tr>
<td>1.97</td>
<td>4.7 x 10^{-18}</td>
<td>5.71 x 10^{-19}</td>
</tr>
<tr>
<td>2.15</td>
<td>9.0 x 10^{-17}</td>
<td>9.0 x 10^{-18}</td>
</tr>
<tr>
<td>2.27</td>
<td>2.9 x 10^{-16}</td>
<td>2.4 x 10^{-17}</td>
</tr>
<tr>
<td>2.85</td>
<td>4.7 x 10^{-15}</td>
<td>2.08 x 10^{-15}</td>
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<tr>
<td>3.07</td>
<td>8.8 x 10^{-15}</td>
<td>4.41 x 10^{-15}</td>
</tr>
<tr>
<td>3.40</td>
<td>1.53 x 10^{-14}</td>
<td>1.18 x 10^{-14}</td>
</tr>
<tr>
<td>3.54</td>
<td>2.3 x 10^{-14}</td>
<td>9.1 x 10^{-15}</td>
</tr>
</tbody>
</table>
The largest cross-sections observed in this experiment are of the order of $10^{-14}$ cm$^2$. The smallest are about $10^{-19}$ cm$^2$. The order of magnitude of the cross-section which is physically expected is about $10^{-16}$ cm$^2$, which is about the cross-sectional area of an atom site. The small cross-sections do not cause concern, for $\Sigma$ can decrease to very low values when the transition from the trap to the band is energetically unfavorable. Cross-sections as large as $10^{-14}$ cm$^2$ must be defended, however. A geometrical cross-section of this magnitude involves a large number of atom sites. Two pieces of evidence reported in the literature support the possibility of large cross-sections. Lax (45) tabulated the capture cross-sections of giant traps in silicon and germanium. Several of these cross-sections were of the order of $10^{-13}$ cm$^2$. Although the liberation cross-section is not necessarily the same as the capture cross-section, the existence of large capture cross-sections gives one some confidence in the possible existence of large liberation cross-sections. The large cross-sections which occur at photon energies above 3.0 ev support a model of an imperfection in diamond proposed by Champion (5). He assumed that aggregates of vacant sites can form in the diamond. The electrons which would normally join in the covalent bonds to the now missing atoms, are less tightly bound, accounting for the 3.0 ev level. This center would act predominantly as a hole trap which, because many vacant sites are involved in
each center, could have a large geometrical cross-section. The large geometrical cross-section might be reflected in a large liberation cross-section. The fact that the cross-section is large for energies greater than 3.0 ev is consistent with the energy level scheme proposed by Champion for this imperfection in diamond.

4. Discussion

Although the interpretation just presented is an attractive one, several difficulties arise when it is considered carefully.

The photon-induced decay constant, B, seems to have approximately the same dependence on photon energy, W, for both D1 and D4 (Figures 22 and 23). One might expect then that the same imperfection is responsible for the large B's in both diamonds. On the first examination, one would think that the same imperfection would have the same cross-section in all cases. The cross-sections for the high photon energies for the two diamonds do not agree within the expected experimental error (see Table 3). This discrepancy can be resolved by the assumption of different size aggregates (different geometrical cross-section) for which the energy levels are in the same position in the band gap.

Another problem with this interpretation is the assumption that $E_1 = KN_t$, where $K$ is a constant independent of time. The internal field is a function of both the amount and the
distribution of the trapped charge. The distribution is lumped into the constant $K$. The assumption that $K$ does not change in time is not necessarily strictly true. This distinct possibility is not included in the simple theory.

Another difficulty arises with this interpretation. The effect of photons on the trapped charges alone have been considered. The photon-induced excitation of electrons from the filled level at 3.0 ev to the conduction band has not been considered. If the concentration of the imperfections is of the order of $10^{15}$ cm$^{-3}$, there are probably many more electrons in this 3.0 ev level than there are trapped holes. Only about $10^{10}$ trapped holes near the diamond surface would be required to generate the internal fields observed in this experiment. Suppose that the cross-sections for the excitation of electrons to the conduction band is of the same order of magnitude as the cross-section for the excitation of electrons from the valence band to the 3.0 ev level (liberation of the trapped hole). Under this supposition, the rate of excitation of electrons to the conduction band (Equation 18 with $P = \Sigma_{\text{e}} \phi$) is greater than the rate of liberation of trapped holes ($P = \Sigma_{\text{h}} \phi$). Since the decay of the internal electric field is certainly dependent on the rate of excitation of charge carriers, one would expect a more rapid decay from the electron excitation process than from the hole liberation (detrapping) process. The results of the simple theory presented with this first interpretation do not apply
to the electron excitation case, because the internal field is generated by trapped charges while the excitation is from normally filled levels. No larger decay constant is observed around 2.4 ev where it would be expected on the assumed energy level scheme (Figure 25, Part A). This energy level scheme could be modified to lower the 3.0 ev level to 2.4 ev. Then the liberation of trapped holes would correspond to the decay constant, B, at about 2.4 ev (Figures 22 and 23, pp. 102, 103) and the electron excitation process would correspond to the decay constant, B, at about 3.0 ev. This possibility is discussed further in the second interpretation. This difficulty with electron excitation from the filled level might also be removed by the assumption of a very small cross-section for this process.

B. The Second Interpretation: Photoconductivity Model

The interpretation to be given here involves only the photon-induced decay results. The dark decay interpretation above is considered to be adequate for the approximate nature of the quantitative results.

1. Qualitative interpretation

The process of photon-induced excitation from the normally filled level to the conduction band is assumed to be much more important than the photon-induced liberation of trapped holes in this second interpretation. In the first interpr
tation, the liberation of trapped holes was considered the more important. The decay of the internal field occurs by the neutralization or annihilation of the trapped charges by the charge carriers excited from the normally filled level.

2. Band model and decay mechanism
   a. Energy level scheme The energy level scheme is shown in Part A of Figure 27. The scheme is only slightly changed from that presented in the discussion of the detrapping model. The filled level about in the middle of the band gap has been lowered to an energy about 2.2 ev above the valence band. On this picture the transition energy from the filled level to the conduction band is 3.2 ev. The large observed B's which result, in a manner to be indicated, from high photoconductivity can then be interpreted readily. The shallow traps remain as before.

   b. Explanation of the decay The explanation of the dark decay is the same as described for the detrapping model. The mechanisms are illustrated in Figure 26. Part B of Figure 27 depicts the situation for the photon-induced decay. The absorption of a photon is accompanied by the excitation (k) of an electron from the deep level to the conduction band. The electron then drifts (m) under the influence of the internal field to the vicinity of a trapped hole on the right. The electron either annihilates (n) the trapped hole or becomes trapped in the neighborhood of the trapped hole.
PART A. ENERGY LEVEL SCHEME FOR DIAMOND.
PHOTOCONDUCTION MODEL

PART B. PHOTON-INDUCED DECAY MECHANISM

Figure 27. Energy level scheme and decay mechanism: photoconduction model.
In either case the trapped hole is effectively neutralized.

3. Quantitative interpretation

The quantitative interpretation is based on the relaxation theory of a homogeneous dielectric medium with a small conductivity as developed in most books dealing with the theory of electricity and magnetism, e.g., Panofsky and Phillips (46). For the present work, the main assumption is that a photoconductivity, \( \sigma_p \), describes the process of interest, and that this photoconductivity obeys Ohm's Law, \( j = \sigma_p E \) where \( j \) is the current density at any point of the medium and \( E \) is the electric field at that point. The combination of one of Maxwell's equations,

\[
\nabla \cdot k \varepsilon_0 E = \rho
\]

with the continuity equation

\[
\nabla \cdot j + \frac{\partial \rho}{\partial t} = 0
\]

and Ohm's Law yields

\[
\nabla \cdot E = (\nabla \cdot E)_{t=0} \exp \left( -\frac{\sigma_p t}{k \varepsilon_0} \right).
\]

(24)

In these expressions \( \rho \) is the true charge density at any point, \( k \) is the dielectric constant of the medium, and \( \varepsilon_0 \) is the usual constant. An assumption which must be made in the course of the derivation is that the conductivity and dielectric constant either do not vary with position, or that they both vary in the same manner with position, so that their ratio is constant with respect to position. The first
alternative is the more likely in the case under consideration. The conductivity induced by photons is probably uniform throughout the diamond because the absorption of the photons is almost constant in the volume. (With only a small amount of absorption, the photon flux density is about constant throughout the volume of the crystal, so the number of photons absorbed in an elemental volume anywhere in the diamond is constant.) If the spatial variation of the internal electric field at the initial time is known, Equation 24 may be integrated to obtain the electric field. Only the time variation of the field is of interest, and this variation is already contained in Equation 24. Therefore, integration is unnecessary. The expression predicts an exponential decay of the internal field as obtained experimentally. The decay constant is

\[ b_p = \frac{\sigma_p}{k \varepsilon_0} \]  

It is interesting to carry the interpretation even further. The conductivity should be

\[ \sigma_p = n e \mu, \]  

where \( n \) is the steady state density of photon liberated carriers, \( e \) is the electronic charge and \( \mu \) is the mobility of the carrier. One would next desire to obtain an expression for the steady state density of carriers. According to Rose (47), the most general relation characterizing photoconductivity is
\[ n = f T, \quad (27) \]

where \( f \) is the excitation rate per unit volume and \( T \) is the lifetime of the carriers in the free states. But

\[ f = N \Sigma \phi, \quad (28) \]

where \( N \) is the density of imperfection centers from which a carrier may be liberated, \( \Sigma \) is the cross-section for the liberation process, and \( \phi \) is the photon flux density. A combination of Equations 25, 26, 27 and 28 yields

\[ b_p = \left( e^{\mu T/k_{\infty}} \right) (N \Sigma) \phi. \quad (29) \]

A linear dependence of \( b_p \) on \( \phi \) is predicted by this theory. This dependence is observed approximately (Appendix E).

One may go one step further. If the wavelength of incident light is such that the absorption coefficient, \( \alpha \), for that light is small, and if the photoconduction transition accounts for all of the absorption, then,

\[ \alpha = N \Sigma. \quad (30) \]

The photon-induced decay constant is thus expected to be directly proportional to \( \alpha \). For a common photon flux density, \( b_p \) should vary directly with \( \alpha \). That is,

\[ B = \left( e^{\mu T/k_{\infty}} \right) (\alpha) \phi_c. \quad (31) \]

In Figure 28 the photon-induced decay constants, \( B \), of the two diamonds have been plotted on a graph of total absorption coefficient versus photon energy. The set of \( B \)'s at different photon energies for the same diamond has been multiplied
Figure 28. Variation of $\alpha$ and $B$ with photon energy.
by a constant factor (different for each set) to obtain values which would "fit" the absorption data. The Type IIa diamond absorption spectrum (from Figure 1-A) is noted by the dotted line. The full line is the Type I diamond absorption spectrum (from Figure 2-A). The adjusted B's tend to increase more rapidly with increasing photon energy than does the dotted line. There is some tendency, however, for the B's to follow the Type I absorption spectrum, specifically the 3 ev (4150Å) system. The results of the fit are not conclusive, however. The rise in B may be a manifestation of the tail of the secondary absorption edge at about 3.8 ev.

At lower W's, Bp is consistently lower than that expected from the optical absorption data. This fact may be explained as follows. The optical absorption data may include the effects of transitions which do not result in excitation of carriers to a band in which they are mobile. But the $\alpha$ measured by a photoconductive technique includes only the effects of transitions which result in free carriers. Therefore, the $\alpha$ determined from a photoconductivity measurement can be smaller than the $\alpha$ measured by the usual optical transmission experiment. It is not strictly correct, of course, to speak of an absorption coefficient in the photoconductive case except in the region of photon energies for which optical absorption results in a free carrier.

To check on the validity of the interpretation, one can calculate approximately the value of $\alpha$ for a particular
wavelength. At 365 millimicrons, \( b_p = 153 \text{ sec}^{-1} \) for \( \phi = 10^{16} \text{ cm}^{-2} \text{ sec}^{-1} \). For diamond, \( k = 5.67 \) (2) and the mobility of both holes and electrons is of the order of \( 10^5 \text{ cm}^2 \text{ volt}^{-1} \text{ sec}^{-1} \). (Moss (2) uses \( \mu = 850 \text{ cm}^2 \text{ volt}^{-1} \text{ sec}^{-1} \), but reported values range from 200 to 4,000 cm² volt⁻¹ sec⁻¹.) The lifetime may be estimated from the work on diamond as a conduction counter. The mean free time before trapping, \( \tau \), from these experiments is of the order of \( 10^{-8} \) seconds. The lifetime, \( T \), in the photoconductivity relation is the total time a carrier spends in the band in which it is mobile, and may be identified with \( \tau \) in this interpretation. Substitution of \( T = 10^{-8} \text{ sec} \) into Equation 31 results in
\[
\alpha = N \Sigma \tau = 0.5 \text{ cm}^{-1}.
\]
This is a reasonable order of magnitude value, consistent with the fact that D1 and D4 are colorless and transparent.

4. Discussion

The second interpretation seems to present a more rigorous and reasonable picture of the decay of the internal field in diamond. The theory is formulated in the framework of classical electric theory. This theory automatically takes into account changes in both distribution and amount of the trapped charge. The theory presented in the first interpretation neglected the effects of temporal variations of the distribution. The order of magnitude of the absorption coefficient calculated from the photoconductivity theory is
clearly reasonable. This photoconductivity theory can account for the small magnitude of the effect of the liberation of trapped charges on the decay. Let subscript 1 refer to the excitation from the filled level and subscript 2 refer to the liberation of trapped charges. Then

\[ \alpha_1 / \alpha_2 = (N_1 / N_2)(\Sigma_1 / \Sigma_2) . \]

If \( \Sigma_1 / \Sigma_2 = 1 \), then

\[ \alpha_1 / \alpha_2 = N_1 / N_2 . \]

But, a reasonable estimate of \( N_1 \) might be \( 10^{15} \) cm\(^{-3} \), while \( N_2 \), the density of trapped charges might be of the order of \( 10^{10} \) cm\(^{-3} \) (based on the magnitude of the internal field). Then

\[ \alpha_1 / \alpha_2 = 10^5 . \]

One could expect the absorption coefficient of trapped charges to be some five orders of magnitude smaller than the \( \alpha \) for the excitation from the filled level. On the plots of \( B \) versus \( W \) (Figures 22 and 23 in Section V), the effect of trapped charges could be responsible for the very small values of \( B \) at photon energies in the range of 2.0 ev.

The assignment of an absorption coefficient to the trapped charge liberation process is not correct, because the \( \alpha_2 \) assigned will vary with time in this case. The variation of \( \alpha_2 \) with time is a result of the variation of the density of trapped charge with time as the trapped carriers are liberated. This difficulty affects the shape of the internal field...
decay but probably does not affect the argument presented in the last paragraph.

The photoconduction model is not in disagreement with Champion's aggregate vacancy theory except in the position of the level. This 3 ev system may still be caused by aggregates of vacant sites and it may well act as a hole trap. No direct experimental evidence, other than the somewhat questionable evidence presented here, is available to locate the position of this level.

The obvious experiment required to further verify the second interpretation has not been performed because it is so difficult in this case. A measurement of the variation of with W is required for the two diamonds studied. Even if these diamonds had large, plane, parallel faces, so that optical absorption measurements on standard equipment would be feasible, only about $2\frac{1}{2}$ per cent of the incident light (after correction for reflection losses) would be absorbed. The facts that the diamonds are small and the faces are not plane makes standard techniques unsuitable.
VII. DISCUSSION

This section is devoted to a discussion of the experiment as a whole. The first part is a critique of the experiment, the second part is a presentation of two problems which arise when the present results are compared with published material.

A. Critique of the Experiment

1. Reproducibility

There are two places where reproducibility is desired: first, in the individual internal field decay runs and second, in the final results. Variations in the two may or may not be related, depending on the nature of these variations.

   a. Individual runs The data of major interest in this experiment is the photon-induced decay data. The reproducibility of this data is important for a determination of the validity of the results. No attempt was made to exactly reproduce the intensity of the monochromatic light at any wavelength, but some runs were taken with sufficiently close intensities that the reproducibility can be observed from the intensity effect plots (Figures 56 through 71, Appendix E). The scatter in these intensity effect plots indicates the lack of complete control over the variables in the experiment. The combination of the expected fluctuations of the photon-induced decay constants, $b_p$, caused by fluctuations in the
counting rate, \( R_1 \), and the expected fluctuations (about 8\%) in the photon flux densities, do not fully account for the scatter in the intensity effect plots (Appendix E) in all cases.

Another indication of the lack of complete reproducibility is given by the dark decay data, which have not been included in this thesis for reasons of spatial economy. Run-to-run fluctuations of 10 to 20\% occurred in both the rate of decay and in the counting rate level at any particular time in the dark decay.

An attempt was made to determine the variable causing this lack of reproducibility. As an aid in the search for the cause, correlations of fluctuations in the different portions of the experiment were investigated. No correlation was observed between fluctuations in the photon-induced decay constant, \( b_p \), and fluctuations in the applied field counting rate at a particular time. No correlation appeared to exist between fluctuations in \( b_p \) and differences in the restoration procedure applied between runs, or between fluctuations in \( b_p \) and the wavelength of the light applied in the preceding run.

The fluctuations in \( b_p \) are difficult to understand. It seems impossible to account for fluctuations in \( b_p \) by random changes in apparatus characteristics. In an auxiliary experiment, the change in \( b_p \) with discrimination level was determined. For D1 a 10\% change in \( b_p \) was observed for an 80\%
change in discrimination level. For D4, a 25% change in decay constant occurred for a 25% change in discrimination level. The observed deviations in $b_p$ were often greater than 25% so even an unreasonable change in either amplifier gain or the discrimination level will not account for the scatter. (The gain and discrimination level are expected to be stable to better than 2%.) Another fact inconsistent with instrumental change as the cause of fluctuations in $b_p$ is that the scatter in the D1 data is greater than that in the D4 data. It seems likely that changes in the diamond are responsible for the fluctuation in $b_p$, but the exact mechanism of the change is unknown.

b. Final results One may get the false impression from the above discussion that the scatter in the data invalidates the results of the experiment. The scatter does make the determination of the intensity effect somewhat uncertain, but the large variation in $B$ with $W$ (Figures 22 and 23) makes the uncertainty in each point relatively less important.

One might point to the discrepancy between the final results (Figure 24) for D1 taken in the different apparatus as proof that the final results are not reproducible. However, as has been already pointed out, the data from Apparatus I could not be corrected for possible variations in intensity, so the results are somewhat more questionable than the results from Apparatus II. There were other differences in the two apparatus which might also influence the results: the trans-
parent electrodes were different, the light paths were differ-
ent, and the diamond was reversed in the holder. The fact
that the variation of B with W is roughly the same for both
diamonds and for D1 in two apparati means that the most sig-
nificant results of the experiment are reasonably repro-
ducible.

2. Validity of the internal field conversion

Some reasons for the possible invalidity of the internal
field conversion of the counting rate decay data are given in
Appendix C. These reasons involve the experimental and theo-
retical aspects of the conversion. Several arguments should
be given to defend the conversion. Certainly, the counting
rate, R₁, is not necessarily a simple function of the inter-
nal field, E₁, so an attempt to convert R₁ to E₁ is important.
The fact that, in most cases, the converted data demonstrate
an exponential decay at the higher internal fields, which are
more reliably known, is a significant point in favor of the
conversion.

Although E₁ may vary with position in the diamond, the
conversion is probably still valid because the processes
resulting in a counting rate tend to average the variation.
Also, only the change in E₁ is required, and the change in
E₁ could well be independent of position. It is also possi-
ble that E₁ is nearly uniform.
3. Discussion of errors

The determination of the errors associated with the measurements reported in this thesis was rather subjective. An attempt was made to apply a 67% criterion to all error determinations, i.e. to assign an error for which there was a 67% probability that the "true" value was within the error value of the observation. In most cases, this assignment was a matter of personal judgement on the part of the author. The assignment of errors could have been more objective by the use of weighted least squares analysis, but the minor influence of the errors on the final results and the probable minor change in the values of the errors did not justify the expenditure of the extra time and effort.

This discussion of errors will describe the propagation of the error in the basic experimental observable, \( R_1 \), through the various parts of the analysis to the final results. The error assigned to \( R_1 \) and the propagation of this error to the value of \( E_1 \) have already been described (Section V). The uncertainties in the values of \( E_1 \) along with the curvature in the photon-induced decay plots made the determination of \( b_p \) from these plots somewhat uncertain. (The uncertainty in the determination of the elapsed time was negligible in comparison with the uncertainty in \( E_1 \).) The error in \( b_p \), which is the absolute value of the slope of the semilogarithmic decay plot, was determined as follows. Two slopes, in addition to the "best" slope already drawn,
were drawn on each decay plot to represent the limiting slopes between which there was a 67% probability that the true slope lay. The absolute values of these slopes were taken as the limits of the error assigned to each $b_p$.

The above determination provided the error flags assigned to the values of $b_p$ plotted in the intensity effect graphs (Figures 56 to 71, Appendix E). In these intensity effect graphs, the photon flux density, $\phi$, calculated from the observed photocell current for each run also is not known exactly. The error in this quantity is discussed in Appendix D. A standard deviation of 10% has been associated with $\phi$ at this point in the analysis. The uncertainties in both $b_p$ and $\phi$ combine to produce an uncertainty in the slope of the straight line which was assumed to fit the data. The slopes of the intensity effect plots were used in the determination of $B$ as a function of $W$, so it was imperative to obtain an estimate of the error in the slope. The determination of this error was again accomplished by an experimental procedure. Limiting slopes, which bounded the region in which there was a 67% probability that the true slope lay, were drawn to provide the error values. The standard deviations in the slopes, obtained in this manner, varied from about 10% to 50% of the best value of the slope. The 6% standard error in the relative values of $\phi$ for the different photon energies (Appendix D) was combined with the standard error in the slope to provide a standard error in $B$ for the
final results. The square root of the sum of the squares of the standard errors of the slope and \( \hat{\phi} \) was taken as the standard error of \( B \). The absolute value of the common photon flux density given on the graph of the final results is uncertain by about 60\% (Appendix D).

The errors quoted in this analysis may be slightly pessimistic, but most of the results are not greatly affected by the size of the standard deviations. Only the interpretation of the photoconductivity around a photon energy of 3.2 eV is made rather difficult by the large uncertainties in that region.

B. Some Puzzles

The remainder of this section will be devoted to the presentation of two problems which arise when the results of the present experiment are compared with published results on diamond.

1. **Relaxation of an internal field by conduction**

   The theory of the relaxation of a homogenous, slightly conducting, dielectric medium has been applied to the results of the photon-induced decay of the internal field. Consideration of a photoconductivity within the framework of the theory led to the interesting and reasonable model presented in Section VI. One may compare the prediction of the original theory with the normal conductivity of diamond reported in
the literature.

The original theory predicts that the internal electric field should decay in time with a time constant, $T_r$, given by

$$T_r = \frac{k \varepsilon_0}{\sigma}$$

where $\sigma$ is the normal dark conductivity of the diamond and $k$ is the dielectric constant. The dielectric constant for diamond is 5.67. The values quoted for the conductivity are often of the order of $10^{-13}$ mho meter$^{-1}$. Equation 32 then gives $T_r = 500$ seconds $\approx 8$ minutes. According to this calculation, the internal field should decay in the dark to $1/e$th of its initial value in that time. This dark decay is not observed. The fast initial decay has a comparable time constant but this decay is not expected to be the manifestation of conduction relaxation for three reasons. First, the fast initial decay is not observed at all in D4. Second, the fast initial decay constant for D1 was different in the two apparati. Third, the fast initial decay accounts for only a part of the total decay of the diamond. One would expect that even though the dark conductivity would change from diamond to diamond (if it is due to imperfection levels), it would be a constant for a particular diamond, and would cause the complete decay of the internal field. The decay would be incomplete only if the imperfection level responsible for conduction were capable of complete depletion. This seems to be a rather remote possibility for the density of trapped
charges is small compared to the usual order of magnitude of imperfection densities.

One may attack the problem from another angle. If diamond is considered to be a large band gap semiconductor, one can calculate the conductivity of the diamond from equations 13.13 and 13.40 in Kittel (1). That diamond is not an intrinsic semiconductor at room temperature is shown by a calculation of the conductivity, $\sigma$, due to thermal excitation of carriers across the band gap of 5.4 ev. If the electron and hole masses are equal to the mass of the free electron, and the mobility is equal to $10^3$ cm$^2$ volt$^{-1}$ sec$^{-1}$, then $\sigma = 5 \times 10^{-44}$ mho cm$^{-1}$. If diamond is considered to have a donor level with a density of $10^{18}$ cm$^{-3}$ and an activation energy of 2.5 ev (about the smallest activation energy consistent with optical absorption data), then the conductivity resulting from thermal excitation of electrons from this level is about $10^{-19}$ mho cm$^{-1}$. The impurity conductivity value is clearly more reasonable than the intrinsic conductivity, but is still orders of magnitude smaller than the experimental value often quoted.

It seems reasonable to conclude that the true conductivity of diamond is even lower than that reported in the literature. It is quite probable that the past measurements have determined a surface conductivity rather than a bulk conductivity for diamond.
2. Detrapping by red light

There are rather numerous reports in the literature concerning the ability of red light (approximately 2.0 ev) to liberate trapped carriers in diamond. The effect has been reported both in the older photoconductivity work (26) and the more recent conduction counting work (29,41). It appears to be well enough substantiated to present an apparent inconsistency with respect to the results reported in this thesis.

There are two possible ways to resolve the problem. The first makes use of the difference in the conditions of measurement between the present work and that previously reported. In all the other experiments the red light was applied while an electric field remained applied to the diamond. In the present work, the applied field was removed and some decay caused by thermal excitation was allowed before light was incident on the diamond. The problem would be resolved if, in photoconduction, the red light acted on the most shallow traps (0.5 ev). These traps would be completely emptied, in the present experiment, by the time the light was applied. The explanation given in the last paragraph suggests that the thermal liberation energy of the trapping site is not equal to the optical liberation energy. This may, in fact, be the case. The optical excitation is so rapid that the neighboring atoms do not achieve thermal equilibrium in the process. For thermal excitation, equilibrium is maintained throughout. This idea is stated in a more rigorous manner as the
Franck-Condon principle (37). Champion and Dale (41) have given some experimental evidence that the thermal liberation energy of the trap emptied by red light is much smaller than the 2.0 ev expected. They estimate, however, that the thermal energy is about 0.8 ev instead of the 0.5 ev required to substantiate the solution already presented.

The inconsistency is also resolved with the aid of the photoconduction interpretation. In the photoconduction model, the contribution of trapped charge liberation to the decay of the internal field is very small. The small values of B (Figures 22 and 23) in the neighborhood of 2.0 ev could be the manifestations of the red light effect.
VIII. CONCLUSIONS AND RECOMMENDATIONS

A. Conclusions

The effect of light on the decay of the internal field in diamond has been measured quantitatively, in terms of a decay constant, for the first time. The internal field was generated by the spatial displacement of trapped electrons from trapped holes in the diamond. The decay constant for red and near infrared illumination was about five orders of magnitude smaller than that for violet and near ultraviolet illumination. Two models of the decay were given. The photoconductivity model appears to be more reasonable than the detrapping model. The photoconductivity model assumes that the rapid decay induced by violet and near ultraviolet illumination is caused by photoconduction arising from the liberation of charge carriers from normally filled levels rather than from levels filled by trapping. Liberation from traps may cause the decay observed in the red light region. In the detrapping model, the decay of the internal field is a result of the liberation of trapped carriers. This model is interesting because it may be analyzed to provide an estimate of the liberation cross-section. It is not possible to determine which model is correct on the basis of present knowledge. An interesting possibility is that the photoconduction model is applicable for large photon energies and the detrapping model for small photon energies.
The method used in this research represents a new approach to the measurement of photoconductivity in diamond and possibly other high resistivity samples. The method is very sensitive and does not require that charge carriers pass through the electrode-diamond boundary. However, the experimental results are obtained slowly.

Another important conclusion derived from the experiment is that the resistivity of diamond is probably considerably higher than is normally considered. The experimental method used in this research may be employed to measure the resistivity of diamond. Since the counting process with an internal electric field is an interior process, the bulk resistivity rather than the surface resistivity will be measured.

B. Recommendations

Several experiments could serve as extensions of this work. The same experiment carried out on more diamonds would be helpful in analyzing the consistency of the results. A measurement of the absorption coefficient for comparison with the results of this polarization decay experiment would be a more critical extension. The measurement of the absorption coefficient may be marginal depending on the diamond chosen for the experiment.

The measurement of the internal field might be attempted by another method. The lifted electrode method used by
Kallmann and Rosenberg (48) was tried with both D1 and D4. For D1, the decay observed with this lifted electrode method was similar to that obtained with the counting rate method. The two methods provided widely variant results for D4. More research is required on this problem.

The following marginal experiments should be considered because of their importance as checks on the interpretations. The first experiment is a measurement of the difference in the absorption of an unpolarized and a polarized diamond. The absorption difference would be obtained as a function of wavelength in the region of expected liberation energies from traps. The other possible experiment is the observation the radiation emitted when charge carriers drop into traps. If the emitted radiation were sufficiently intense, the radiation might be spectrally analyzed to determine the wavelengths of maximum emission.
IX. LITERATURE CITED


X. ACKNOWLEDGMENTS

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XI. APPENDICES

A. Appendix A: Apparatus I.

The apparatus to be described in this section was used in the preliminary investigation of Diamond One. A large part of the equipment used in Apparatus II was employed in this apparatus, but there were some significant differences in the components. Only the different components will be described in this Appendix. Apparatus I can be broken down into the same major parts as Apparatus II: the basic counting system, the count recording equipment, and the source of controlled illumination. For Apparatus I, each of these major parts serves the purpose already described for it in Section II.

1. Description of the components

a. Basic counting system  
The names given to the components of this system are the same as used in the description of Apparatus II, but the actual components were in two cases quite different.

   (1) Source of gamma rays  
The same gamma source used in Apparatus II was employed in this system. The mechanism for the introduction of motion to the source was quite different. The source cylinder was attached to a 4 inch arm which projected perpendicularly from an axle mounted in steel plates on opposite sides of a lead brick. Manual rotation
of the axle caused the gamma source to travel in a vertical circle from one position, directly over and about one inch from the diamond, to another in which it was shielded from the diamond by four inches of lead brick. These two positions were the limits of motion for the mechanism, and thus they were very reproducibly and rapidly attained.

(2) **Diamond holder**  This component was quite different from its counterpart in Apparatus II, but its purpose was still the same. The diamond holder for Apparatus I is shown in Figure 29. The transparent electrode for Apparatus I was a screen of fine wires. The screen was designed to approximate the electrical properties of a solid electrode while still allowing monochromatic light to strike the diamond. This screen was constructed of 5 mil molybdenum wires spotwelded to a #18 nichrome wire frame approximately 1/2 inch by 9/16 inch. The 5 mil wires were separated by an average distance of 1/32 inch along the longer side. The diamond was held by spring action between this transparent electrode and a one inch piece of #12 copper wire soldered directly to the grid lug of the first vacuum tube in the pre-
preamplifier. A piece of aluminum foil, cut to the shape of the diamond face, was attached to the diamond by a coating of Aquadag. The aluminum foil electrode made contact with the copper lug when the diamond was inserted in the holder.

b. **The count recording equipment**  There were two differences from Apparatus II in this equipment. A pre-
Figure 29. Top view of diamond holder, mirror and photo-electric device.
preamplifier was used along with the preamplifier and amplifier in this equipment, and a different discriminator circuit was employed.

The pre-preamplifier consisted of one stage of amplification feeding a cathode follower output state. The stage of amplification was a pentode-connected 6AK5 vacuum tube. The cathode follower was a triode-connected 6AK5. The component had a gain of about 4.5. The signal from the pre-preamplifier was fed to the preamplifier.

The discriminator was more sensitive than its successor, but it also was less stable. In Apparatus II, the stability of the discriminator was considered to be more important than the sensitivity.

c. Source of controlled illumination The monochromator and primary light sources used in this apparatus were those described in Section II-B. A 929 photoelectric cell was used to measure the intensity of the monochromatic light beam in this apparatus, as it was in Apparatus II. A front surfaced aluminum mirror was used in conjunction with the photocell in this equipment. When a measurement of the intensity was desired, this mirror was rotated into the light beam, which normally fell directly on the diamond in its holder. Figure 29 shows the relative positions of the important components. The mirror directed the beam onto the photocathode. An R.C.A. dc microammeter (model WV-84A) was used to measure the photocell current. A battery pack
supplied the required potential difference.

2. Component relationships

The diamond holder, the pre-preamplifier, the photocell and mirror, and the electrode potential switch were all housed in a copper box called the diamond chamber. The first three components mentioned were located in the upper portion of this box, while the switch was located in a lower compartment. The diamond chamber was attached directly to the monochromator, such that an entrance port abutted the output of the monochromator. The light beam was incident on the front, vertical face of the diamond through the transparent electrode. The gamma rays entered the diamond from the top.

B. Appendix B: Synopsis of Experimental Data

A synopsis of the experimental data is presented in this section. Examples of the semi-logarithmic plots of the photon-induced decay portions of many typical runs are given on the following pages.

Figures 30 through 35 present the photon-induced decay (Region III) portions of typical runs on D1 in Apparatus I for several light intensities and wavelengths. The starting point for each photon-induced decay portion is noted as a vertical dotted line except where this line coincides with the ordinate axis. The solid line, denoting the variation of the counting rate with time, has been drawn to join to
the points (not shown) at the start of the photon-induced decay. Table 4 presents a tabulation of the photon-induced decay constants ($b_p'$) of all runs on D1 in Apparatus I. Table 4 also presents the observed photocell current ($J$) for each run.

Figures 36 through 45 present the data for most of the runs on D1 in Apparatus II in the same manner as described above. Table 5 is a tabulation of the results for all runs on D1 in Apparatus II.

Figures 46 through 53 present the data for many of the runs on D4 in Apparatus II. Table 6 summarizes the results for all runs on D4.
Figure 30. Examples of photon-induced decay with 365 millimicron light for D1 in Apparatus I.
Figure 31. Examples of photon-induced decay with 404 millimicron light for DI in Apparatus I.
Figure 38. Examples of photon-induced decay with 435 millimicron light for D1 in Apparatus I.
Figure 33. Examples of photon-induced decay with 475 millimicron light for DI in Apparatus I.
Figure 34. Examples of photon-induced decay with 546 millimicron light for D1 in Apparatus I.
Figure 35. Examples of photon-induced decay with 578 millimicron light for DI in Apparatus I.
Table 4. Synopsis of photon-induced decay data on Dl in Apparatus I

<table>
<thead>
<tr>
<th>Wavelength in millimicrons</th>
<th>Run no.</th>
<th>Photon-induced decay constant, $b'_p$ (min$^{-1}$)</th>
<th>Average photocell current, $J$ (µamp)</th>
</tr>
</thead>
<tbody>
<tr>
<td>365</td>
<td>1-74</td>
<td>0.56 ± 0.06</td>
<td>0.180 x 0.01</td>
</tr>
<tr>
<td></td>
<td>1-73</td>
<td>1.11 ± 0.20</td>
<td>0.307</td>
</tr>
<tr>
<td></td>
<td>1-72</td>
<td>1.31 ± 0.15</td>
<td>0.335</td>
</tr>
<tr>
<td></td>
<td>1-78</td>
<td>1.84 ± 0.46</td>
<td>0.373</td>
</tr>
<tr>
<td></td>
<td>1-66</td>
<td>1.36 ± 0.18</td>
<td>0.405</td>
</tr>
<tr>
<td></td>
<td>1-77</td>
<td>2.07 ± 0.21</td>
<td>0.460</td>
</tr>
<tr>
<td></td>
<td>1-75</td>
<td>1.86 ± 0.47</td>
<td>0.540</td>
</tr>
<tr>
<td></td>
<td>1-76</td>
<td>3.20 ± 0.36</td>
<td>0.569</td>
</tr>
<tr>
<td>404</td>
<td>1-60</td>
<td>0.138 ± 0.009</td>
<td>0.128</td>
</tr>
<tr>
<td></td>
<td>1-47</td>
<td>0.083 ± 0.005</td>
<td>0.150</td>
</tr>
<tr>
<td></td>
<td>1-37</td>
<td>0.071 ± 0.004</td>
<td>0.135</td>
</tr>
<tr>
<td></td>
<td>1-32</td>
<td>0.114 ± 0.004</td>
<td>0.228</td>
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<tr>
<td></td>
<td>1-55</td>
<td>0.445 ± 0.088</td>
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<tr>
<td></td>
<td>1-46</td>
<td>0.300 ± 0.050</td>
<td>0.292</td>
</tr>
<tr>
<td></td>
<td>1-70</td>
<td>0.926 ± 0.160</td>
<td>0.355</td>
</tr>
<tr>
<td></td>
<td>1-53</td>
<td>0.704 ± 0.066</td>
<td>0.348</td>
</tr>
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<td></td>
<td>1-68</td>
<td>0.525 ± 0.066</td>
<td>0.365</td>
</tr>
<tr>
<td></td>
<td>1-69</td>
<td>0.660 ± 0.077</td>
<td>0.380</td>
</tr>
<tr>
<td></td>
<td>1-71</td>
<td>1.08 ± 0.15</td>
<td>0.583</td>
</tr>
<tr>
<td></td>
<td>1-51</td>
<td>0.853 ± 0.301</td>
<td>0.403</td>
</tr>
<tr>
<td></td>
<td>1-79</td>
<td>0.700 ± 0.048</td>
<td>0.438</td>
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<tr>
<td></td>
<td>1-80</td>
<td>0.934 ± 0.073</td>
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</tr>
<tr>
<td>435</td>
<td>1-38</td>
<td>0.074 ± 0.010</td>
<td>0.188</td>
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<tr>
<td></td>
<td>1-23</td>
<td>0.083 ± 0.007</td>
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</tr>
<tr>
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<td>1-20</td>
<td>0.087 ± 0.008</td>
<td>0.338</td>
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<tr>
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<td>1-59</td>
<td>0.234 ± 0.021</td>
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<tr>
<td></td>
<td>1-57</td>
<td>0.335 ± 0.023</td>
<td>0.425</td>
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<tr>
<td></td>
<td>1-35</td>
<td>0.258 ± 0.033</td>
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</tr>
<tr>
<td></td>
<td>1-29</td>
<td>0.402 ± 0.051</td>
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</tr>
<tr>
<td></td>
<td>1-25</td>
<td>0.509 ± 0.078</td>
<td>0.790</td>
</tr>
<tr>
<td>450</td>
<td>1-48</td>
<td>0.120 ± 0.018</td>
<td>0.370</td>
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<tr>
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<td>1-50</td>
<td>0.174 ± 0.021</td>
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<td>1-40</td>
<td>0.214 ± 0.031</td>
<td>0.925</td>
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<tr>
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<td>1-44</td>
<td>0.384 ± 0.055</td>
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<tr>
<td>475</td>
<td>1-61</td>
<td>0.025 ± 0.004</td>
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</tr>
<tr>
<td></td>
<td>1-41</td>
<td>0.153 ± 0.012</td>
<td>0.938</td>
</tr>
<tr>
<td></td>
<td>1-42</td>
<td>0.234 ± 0.025</td>
<td>0.948</td>
</tr>
<tr>
<td></td>
<td>1-43</td>
<td>0.176 ± 0.014</td>
<td>0.975</td>
</tr>
<tr>
<td>Wavelength in millimicrons</td>
<td>Run no.</td>
<td>Photon-induced decay constant, $b_p$ (min(^{-1}))</td>
<td>Average photon-cell current, $J$ ((\mu)amp)</td>
</tr>
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<td>--------</td>
<td>---------------------------------</td>
<td>---------------------------------</td>
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<tr>
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<td>1-49</td>
<td>0.207 ± 0.021</td>
<td>1.20 x 0.01</td>
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<tr>
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<td>1-39</td>
<td>0.169</td>
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<td>1-63</td>
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<td>1-28</td>
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<td>0.395</td>
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<td>1-52</td>
<td>0.112</td>
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<td>1-31</td>
<td>0.150</td>
<td>0.513</td>
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<tr>
<td></td>
<td>1-26</td>
<td>0.171</td>
<td>0.605</td>
</tr>
</tbody>
</table>
Figure 36. Examples of photon-induced decay with 350 millimicron light for Dl in Apparatus II.
Figure 57. Examples of photon-induced decay with 365 millimicron light for D1 in Apparatus II.
Figure 38. Examples of photon-induced decay with 404 millimicron light for D1 in Apparatus II.
Figure 39. Examples of photon-induced decay with 435 millimicron light for DI in Apparatus II.
Figure 40. Examples of photon-induced decay with 450 millimicron light for D1 in Apparatus II.
Figure 41. Examples of photon-induced decay with 546 millimicron light for Dl in Apparatus II.
Figure 42. Examples of photon-induced decay with 578 millimicron light for D1 in Apparatus II.
Figure 43. Examples of photon-induced decay with 630 millimicron light for Dl in Apparatus II.
Figure 44. Examples of photon-induced decay with 670 millimicron light for D1 in Apparatus II.
Figure 45. Examples of photon-induced decay with 750 millimicron light for DI in Apparatus II.
Table 5. Synopsis of photon-induced decay data on Dl in Apparatus II

<table>
<thead>
<tr>
<th>Wavelength in millimicrons</th>
<th>Run no.</th>
<th>Photon-induced decay constant, ( b' ) (min(^{-1}))</th>
<th>Average photocell current, ( J ) (( \mu ) amp)</th>
</tr>
</thead>
<tbody>
<tr>
<td>350</td>
<td>1-124</td>
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<td>0.875 x 0.01</td>
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<td>1-120</td>
<td>0.952</td>
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<tr>
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<td>1-112</td>
<td>0.143</td>
<td>0.320</td>
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<tr>
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<td>1-114</td>
<td>0.421</td>
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<tr>
<td>404</td>
<td>1-118</td>
<td>0.161</td>
<td>0.420</td>
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<tr>
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<td>1-116</td>
<td>0.437</td>
<td>0.840</td>
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<td>1-132</td>
<td>0.205</td>
<td>0.650</td>
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<td>1-123</td>
<td>0.123</td>
<td>0.845</td>
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<td>1-111</td>
<td>0.299</td>
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<td>1-110</td>
<td>0.714</td>
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<td>450</td>
<td>1-122</td>
<td>0.0834</td>
<td>1.10</td>
</tr>
<tr>
<td></td>
<td>1-121</td>
<td>0.358</td>
<td>3.30</td>
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<tr>
<td>546</td>
<td>1-115</td>
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<td>630</td>
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<td>1-129</td>
<td>0.0513</td>
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<td></td>
<td>1-127(_b)</td>
<td>0.163</td>
<td>99.0</td>
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<tr>
<td>750</td>
<td>1-128</td>
<td>0.0224</td>
<td>95.0</td>
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<tr>
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<td>1-125</td>
<td>0.166</td>
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</table>
Figure 46. Examples of photon-induced decay with 350 millimicron light for D4 in Apparatus II.
Figure 47. Examples of photon-induced decay with 365 millimicron light for D4 in Apparatus II.
Figure 48. Examples of photon-induced decay with 404 millimicron light for D4 in Apparatus II.
Figure 49. Examples of photon-induced decay with 455 millimicron light for D4 in Apparatus II.
Figure 60. Example a of photon-induced decay with 546 millimicron light for D4 in Apparatus II.
Figure 51. Examples of photon-induced decay with 578 millimicron light for D4 in Apparatus II.
Figure 52. Examples of photon-induced decay with 630 millimicron light for D4 in Apparatus II.
Figure 55. Examples of photon-induced decay with 670 millimicron light for D4 in Apparatus II.
<table>
<thead>
<tr>
<th>Wavelength in millimicrons</th>
<th>Run no.</th>
<th>Photon-induced decay constant, ( b_p ) (min(^{-1}))</th>
<th>Photocell current, ( J ) (( \mu )amp)</th>
</tr>
</thead>
<tbody>
<tr>
<td>350</td>
<td>4-42</td>
<td>0.199 ± 0.015</td>
<td>0.265 x 0.10</td>
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<tr>
<td></td>
<td>4-52</td>
<td>0.514 ± 0.053</td>
<td>0.700</td>
</tr>
<tr>
<td>365</td>
<td>4-37</td>
<td>0.318 ± 0.033</td>
<td>0.161</td>
</tr>
<tr>
<td></td>
<td>4-35</td>
<td>0.706 ± 0.084</td>
<td>0.324</td>
</tr>
<tr>
<td></td>
<td>4-40</td>
<td>0.703 ± 0.074</td>
<td>0.340</td>
</tr>
<tr>
<td>404</td>
<td>4-34</td>
<td>0.356 ± 0.014</td>
<td>0.468</td>
</tr>
<tr>
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<td>4-54</td>
<td>0.429 ± 0.063</td>
<td>0.648</td>
</tr>
<tr>
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<td>4-55</td>
<td>0.354 ± 0.040</td>
<td>0.660</td>
</tr>
<tr>
<td></td>
<td>4-53</td>
<td>0.542 ± 0.036</td>
<td>0.719</td>
</tr>
<tr>
<td></td>
<td>4-39</td>
<td>0.677 ± 0.039</td>
<td>0.725</td>
</tr>
<tr>
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<td>4-35</td>
<td>0.455 ± 0.052</td>
<td>0.780</td>
</tr>
<tr>
<td></td>
<td>4-38</td>
<td>0.712 ± 0.067</td>
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<tr>
<td>435</td>
<td>4-41</td>
<td>0.254 ± 0.057</td>
<td>0.582</td>
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<tr>
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<td>4-27</td>
<td>0.326 ± 0.037</td>
<td>0.826</td>
</tr>
<tr>
<td></td>
<td>4-48</td>
<td>0.409 ± 0.044</td>
<td>0.980</td>
</tr>
<tr>
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<td>4-36</td>
<td>0.769 ± 0.042</td>
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<td>4-28</td>
<td>0.641 ± 0.045</td>
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<td>0.0530 ± 0.0094</td>
<td>2.29</td>
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<td>4-30</td>
<td>0.0545 ± 0.0110</td>
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<td>4-31</td>
<td>0.0514 ± 0.0055</td>
<td>4.78</td>
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<td>4-29</td>
<td>0.0740 ± 0.0087</td>
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<td>0.00280 ± 0.00062</td>
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<td>4-43</td>
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<td>4-44</td>
<td>0.103 ± 0.010</td>
<td>1.59</td>
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<tr>
<td>600</td>
<td>4-32</td>
<td>0.140 ± 0.029</td>
<td>35.6</td>
</tr>
<tr>
<td>630</td>
<td>4-45</td>
<td>0.0250 ± 0.0024</td>
<td>6.15</td>
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<td></td>
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<td>0.0316 ± 0.0037</td>
<td>8.65</td>
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<td>670</td>
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<td>0.00970 ± 0.00024</td>
<td>7.20</td>
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<td></td>
<td>4-47</td>
<td>0.0231 ± 0.0021</td>
<td>15.5</td>
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<td>750</td>
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<td>0.00196 ± 0.00030</td>
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<td>825</td>
<td>4-47</td>
<td>0.00245 ± 0.00037</td>
<td>14.5</td>
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</table>
C. Appendix C: Dependence of the Counting Rate on Electric Field

Knowledge of the dependence of the counting rate, \( R_1 \), on the internal electric field, \( E_1 \), is a requisite for the data analysis described in Section V. This knowledge was gained from the auxiliary experiment described in this appendix.

1. The basic method

The ideal way to determine the relation of \( R_1 \) to \( E_1 \) is to observe \( R_1 \) directly as \( E_1 \) is varied. No way is known, however, to measure directly \( E_1 \) in a diamond. An indirect approach is therefore necessary. The assumption which allows the determination of the relation is that the counting rate is the same function of \( E_1 \) alone that it is of an applied electric field, \( E_a \), in the absence of \( E_1 \). Under this assumption, the observation of the initial \( R_1 \) (while \( E_1 = 0 \)) for different \( E_a \) determines the relationship which also holds for \( E_1 \). The experiment, observation of the initial \( R_1 \) for various known applied voltages, is quite simple in principle. However, the complicating phenomenon of polarization must be either avoided or taken into account. An attempt was made to avoid polarization in this auxiliary experiment, but it was not entirely successful, so corrections for the polarization had to be made. A detailed treatment is given below.
2. Apparatus and procedure

This auxiliary experiment was performed in the same apparatus used for the main experiment. For the smaller applied voltages, a battery pack and voltage divider were substituted for the electronic, high voltage supply.

A standard procedure, described in this paragraph, was used for the observation at each applied voltage. Once the voltage to be applied was set with the aid of the meter on the power supply, the voltage was applied to the diamond, the gamma source was moved to its "count" position, and the scaler was activated. These steps were executed in rapid succession. The applied field counting rate, \( R_a \), was observed for a 60 second period at the end of which only the scaler was deactivated. After \( R_a \) was recorded, and always within 30 seconds of the end of the \( R_a \) determination, an observation of the \( R_1 \) was made to determine the size of the \( E_i \) built up during the short applied field counting period. The following steps were taken in rapid succession to initiate the internal field counting rate observation: the amplifier polarity was changed, the transparent electrode was switched from applied potential to ground potential, and the scaler was activated. The gamma source was left in its "count" position throughout both the applied field and internal field counting periods. The internal field counting rate was observed for 30 seconds, after which the scaler
was deactivated and the gamma source was moved to its shielded position until the next voltage was applied. In order to remove any persistent internal field, the diamond was illuminated with intense 365 or 578 millimicron light for about one minute between voltage applications. (Both wavelengths appeared to have the same desired effect.) This intense light was known to cause the complete decay of the internal field in a much shorter time than was used in this depolarization application. As a further precaution, the observations were usually taken in order of increasing voltage so that any internal field unknowingly remaining after the light treatment would have only a small influence on the next higher applied voltage determination. In addition to these precautions, check points were taken at the lower applied voltages after some of the observations at the high applied voltages.

3. Presentation and analysis of the data

The initial $R_a$ for various applied voltages are tabulated for D1 in Table 7 and for D4 in Table 8. The internal field counting rates, $R_i$, obtained at the end of the $R_a$ observations are also given. The numbers from different runs are coded in the extreme right-hand column, and differences in the runs are noted in the key at the end of each table. The fact that an appreciable $E_i$ was present after only 90 seconds of counting under applied field conditions is probably a result of
Table 7. Counting rates for DI for various applied voltages

<table>
<thead>
<tr>
<th>Applied voltage (volts)</th>
<th>Applied field counting rate, $R_a$ (units minute$^{-1}$)</th>
<th>Internal field counting rate, $R_1$ (units minute$^{-1}$)</th>
<th>Run</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>$0.03 \pm 0.03$</td>
<td>$0.03 \pm 0.04$</td>
<td>3</td>
</tr>
<tr>
<td>6</td>
<td>$0.09$</td>
<td>$0.03$</td>
<td>3</td>
</tr>
<tr>
<td>8</td>
<td>$0.65$</td>
<td>$0.06$</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>$0.75$</td>
<td>$0.16$</td>
<td>3</td>
</tr>
<tr>
<td>10</td>
<td>$1.34$</td>
<td>$0.16$</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>$2.09$</td>
<td>$0.00$</td>
<td>1</td>
</tr>
<tr>
<td>15</td>
<td>$5.25$</td>
<td>$0.13$</td>
<td>3</td>
</tr>
<tr>
<td>20</td>
<td>$10.90$</td>
<td>$0.00$</td>
<td>1</td>
</tr>
<tr>
<td>30</td>
<td>$16.91$</td>
<td>$0.16$</td>
<td>2</td>
</tr>
<tr>
<td>50</td>
<td>$27.26$</td>
<td>$2.69$</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>$28.69$</td>
<td>$1.38$</td>
<td>2</td>
</tr>
<tr>
<td>100</td>
<td>$43.28$</td>
<td>$7.94$</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>$41.12$</td>
<td>$9.75$</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>$47.91$</td>
<td>$5.78$</td>
<td>2</td>
</tr>
<tr>
<td>150</td>
<td>$53.48$</td>
<td>$16.06$</td>
<td>1</td>
</tr>
<tr>
<td>200</td>
<td>$59.78$</td>
<td>$20.63$</td>
<td>1</td>
</tr>
<tr>
<td>300</td>
<td>$66.70$</td>
<td>$31.63$</td>
<td>1</td>
</tr>
<tr>
<td>420</td>
<td>$72.82$</td>
<td>$39.06$</td>
<td>1</td>
</tr>
<tr>
<td>510</td>
<td>$82.06$</td>
<td>$40.44$</td>
<td>1</td>
</tr>
</tbody>
</table>

1 - First run, 365 millimicrons  
2 - Second run, 578 millimicrons  
3 - Third run, 365 millimicrons

$^a$ One unit equals 32 counts.
Table 8. Counting rates for D4 for various applied voltages

<table>
<thead>
<tr>
<th>Applied voltage (volts)</th>
<th>Applied field counting rate, $R_a$ (units minute$^{-1}$)$^a$</th>
<th>Internal field counting rate, $R_i$ (units minute$^{-1}$)$^a$</th>
<th>Run$^b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>6.56 ± 0.45</td>
<td>0.19 ± 0.11</td>
<td>2</td>
</tr>
<tr>
<td>20</td>
<td>20.28</td>
<td>0.56 ± 0.19</td>
<td>1</td>
</tr>
<tr>
<td>25</td>
<td>27.44</td>
<td>2.25 ± 0.37</td>
<td>2</td>
</tr>
<tr>
<td>30</td>
<td>30.00</td>
<td>1.81 ± 0.33</td>
<td>1</td>
</tr>
<tr>
<td>40</td>
<td>36.12</td>
<td>2.63 ± 0.41</td>
<td>1</td>
</tr>
<tr>
<td>50</td>
<td>39.81, 41.60</td>
<td>3.44 ± 0.46</td>
<td>1</td>
</tr>
<tr>
<td>75</td>
<td>44.70</td>
<td>10.06 ± 0.80</td>
<td>2</td>
</tr>
<tr>
<td>100</td>
<td>50.00</td>
<td>11.31 ± 0.84</td>
<td>1</td>
</tr>
<tr>
<td>150</td>
<td>56.56</td>
<td>16.19 ± 1.01</td>
<td>2</td>
</tr>
<tr>
<td>200</td>
<td>56.00</td>
<td>20.06 ± 1.11</td>
<td>1</td>
</tr>
<tr>
<td>250</td>
<td>58.16</td>
<td>23.88 ± 1.21</td>
<td>2</td>
</tr>
<tr>
<td>300</td>
<td>60.00</td>
<td>22.19 ± 1.17</td>
<td>1</td>
</tr>
<tr>
<td>360</td>
<td>61.16</td>
<td>23.19 ± 1.20</td>
<td>2</td>
</tr>
<tr>
<td>400</td>
<td>60.10</td>
<td>25.25 ± 1.25</td>
<td>1</td>
</tr>
<tr>
<td>450</td>
<td>61.38</td>
<td>28.06 ± 1.32</td>
<td>2</td>
</tr>
<tr>
<td>750</td>
<td>64.88</td>
<td>31.69 ± 1.40</td>
<td>2</td>
</tr>
</tbody>
</table>

$^a$One unit equals 32 counts.

$^b$Run one preceded run two by roughly three hours. The experimental conditions were the same for both runs.
the phenomenon of dark polarization discussed in Appendix F. This dark polarization is assumed to be an internal field created, in the absence of ionization, by trapped charges. The dark polarization grew very rapidly on the application of a voltage so it is reasonable to assume that an internal field (i.e., the dark polarization) was present throughout the applied field counting period. Then the effective field, $E_e$, which acted on the liberated electrons was smaller than $E_a$. Because $R_a$ as a function of $E_e$ was desired, a correction for this dark polarization effect had to be made. Two assumptions were made to perform this correction. First, the variation of $R_a$ with $E_e$ was assumed to be the same as the variation of $R_i$ with $E_i$. The other assumption was that Equation 13 holds.

$$E_e = E_a - E_i.$$  \hspace{1cm} (13)

The correction was made as follows. The plot of the data given in Table 7 (or 8) was considered to be a first approximation to the desired corrected curve. The applied field counting rate, $R_a$, and the corresponding $R_i$ for a particular applied voltage were considered. On the basis of the first assumption, the value of $E_i$ corresponding to $R_i$ was obtained from the approximate curve. The value of $E_e$ was determined then from Equation 13, since $E_a$ was known. This procedure was followed for each counting rate point. Upon completion, $R_i$ was plotted versus the new, approximate $E_e$ to provide a
second approximation to the desired curve. The entire process was repeated until differences in the successive approximate curves were smaller than experimental deviations would allow.

4. Results

The corrected curves of $R_a$ versus $E_e$ are given for D1 and D4 as Figures 54 and 55 respectively. The fields were obtained from the corrected applied voltage by dividing the voltages by the average thickness of the diamond. Enlargements of these curves for the lower electric field region were used in the data analysis described in Section V. It should be noted that these curves are the "true" curves only for one set of instrument settings (amplifier gain and discriminator level). The settings (gain = $6 \times 10^4$, discrimination level = 7.2 volts) used for the observation of these data were the same as those used throughout the main experiment on each diamond. The shape of the curves is that to be expected, roughly, from the theory of pulse heights. At the higher electric fields, all of the gamma-ray-liberated electrons and holes are drawn to the electrodes, so the counting rate is independent of $E_a$. The change noted in the actual graphs is probably due to the non-ideal conditions which have already been mentioned (Section I-B).

5. Discussion

Two topics will be covered in this section: experi-
Figure 54. Variation of counting rate with electric field for DI.
Figure 55. Variation of counting rate with electric field for D4.
mental problems which affect the results given above will be
discussed first, followed by a discussion of the assumptions
underlying the final results.

a. Experimental problems Reliable counting rate
observations at the very low applied electric fields were
very difficult to obtain. Not only is the statistical fluc­
tuation in the true counting rate high, but the effect of
noise on the observation is exaggerated. Continuous moni­
toring of the amplified pulses with the oscilloscope allowed
the observation of the most obvious noise pulses. It was
difficult to tell many of the noise pulses from the diamond
pulses because the amplifier shapes all pulses to look about
the same. It was possible to account for the quantitative
contribution of these noise pulses only by observation of
the background counting rate with the gamma source in its
shielded position. The average background counting rate was
measured at several times during the runs and was subtracted
off in the usual manner. Several runs on different days were
taken to provide data from which an average dependence of $R_a$
on small $E_e$ could be derived.

Another experimental problem involved only Dl. Both
the $R_a$ and the $R_l$ for this diamond changed during the obser­
vation period at a single voltage. Since the rate of change
was not necessarily the same for both portions, the right
procedure for correction for the internal field was in doubt.
The correction procedure used (that given in subsection 3 of
this appendix) assumes that Equation 13 is valid for time average values of $E_e$ and $E_1$. The quality of this assumption is unknown. This uncertainty does not drastically affect the portion of the $R_a$ versus $E_e$ curve used in the analysis of the decay data from the main experiment because considerable internal fields occur only for the higher applied fields.

b. Discussion of assumptions underlying the results

The main assumption made in this auxiliary experiment was that the variation of $R_1$ with $E_1$ is the same as the variation of $R_a$ with $E_e$. There are several reasons to suspect that this is not necessarily true.

The first reason concerns the variation of the two fields with position in the diamond. The applied field is independent of position in an infinite, homogeneous slab of diamond, but the internal electric field could, in general, vary with position depending on the spatial distribution of the trapped charges. (Two distributions, all charges trapped at the surfaces and a uniform dipole distribution throughout the volume, will give internal fields independent of position.) If the internal field does vary with position, then the internal field counting rate measures some weighted average field. A counting rate taken with a uniform electric field which is equal to this average field may not be equal to the internal field counting rate. The conversion of the counting rates to internal fields in the analysis may then
refer to some weighted average field rather than to a truly uniform field.

There is another fundamental difference between $R_a$ and $R_1$. The number of available traps is different in the two cases. Most traps are presumably empty in the applied field case, but many traps are necessarily full in the internal field case because the internal field is generated by trapped charges. A difference in the number of available trapping sites is reflected in a difference in $\tau$, the mean free time before trapping, in the two cases. Since the pulse height depends on $\tau$ as well as the electric field, the pulse heights, and therefore the counting rates, will be different for the two cases even when the electric fields are equal. It is quite likely, however, that the number of filled trapping sites is orders of magnitude smaller than the number of available trapping sites so that little if any effect should be noted from this possible difference.

D. Appendix D: Determination of the Photon Flux Density from the Observed Photocell Current

In the body of the thesis, the photon flux density, $\Phi_i$, incident on the diamond was required to determine the effect of the intensity on the photon-induced decay. It was also used to refer the decay data at the various photon energies, $W$, to a common photon flux density, $\Phi_C$, whose absolute value was desired for numerical computations. The determination
will be described first for an idealized situation in order to show the basic considerations. The actual situation will then be discussed.

1. **Photon flux density determination for the idealized situation**

   a. **The idealized situation** The situation envisaged here is the following. The monochromatic beam from the monochromator is directed by the mirror to the NESA glass plate, which is uniformly illuminated over a half-inch-square area. The diamond is approximately centered in this area. When the mirror is rotated 90 degrees, the entire light beam is incident on the window of the measuring photocell.

   b. **Determination of the photon flux density** A photoelectric cell measures the number of photons per second striking the photocathode. If the glass envelope of the photocell is coated with an opaque covering except for a window of area $A$ situated so that light incident on the window also strikes the photocathode, then the photocell measures the rate, $M$, at which photons are incident on the window. The relation between $M$ and the total photocell current, $J$, is

   \[ J = SM, \]

   where $S$ is the photocell sensitivity. This sensitivity varies with $\lambda$ (i.e. with wavelength). For the idealized situation above, $\phi_1$ is constant over $A$, so that $M = \phi_1A$, and

   \[ \phi_1 = J/SA. \]

\[ \text{(33)} \]

\[ \text{(34)} \]
Since \( J \) can be measured, a knowledge of \( S \) allows the determination of \( \phi_1 \). The sensitivity was obtained from a calibration experiment, the details of which are given in subsection 3 of this appendix. The value of \( \phi_1 \) given above is that incident on the NESA glass plate. The photon flux density, \( \phi \), entering the diamond is obtained by correction for the reflection and absorption losses of the NESA glass plate and the reflection loss at the diamond:

\[
\phi = (t)(1-r) \phi_1 ,
\]

where \( t \) is the transmittance of the NESA glass plate, and \( r \) is the reflectance of the diamond. Both \( t \) and \( r \) are functions of \( W \). The reflectance may be obtained from the refractive index by the relation (49)

\[
r = (n-1)/(n+1)
\]

if normal incidence is assumed.

2. Photon flux density determination for the actual situation

The actual situation was different from the idealized situation in only one major aspect. The monochromatic beam was not equally intense over its half inch square area. This effect was observed with both the mercury arc source and the incandescent source, and the variation was different for the two sources. In both cases this effect varied with intensity. The rate of incidence of photons on the photocell window for this situation is

\[
M = \int_A \phi_1 \, dA ,
\]
where \( \phi \) is the photon flux density striking the element of area \( dA \) in the beam whose total area is \( A \). The photon flux density at the diamond cannot be obtained from \( J \) alone. The auxiliary experiment described in the next paragraph was devised to correct this condition.

The most direct method was used to accomplish the correction. A cardboard mask with a 3/16 inch square window, designated by its area \( A_w \) (about the size and shape of DI), was placed in a position to intercept the same portion of the beam area as did the diamonds normally. A second photocell was placed behind the mask to determine the photon rate through \( A_w \). The original photocell used to measure the total photon rate during the internal field decay runs was in its normal position. The experiment consisted of a measurement of \( J \) from each photocell at various intensities for all wavelengths of interest. The indexed mirror assembly made the experiment easy to do.

The analysis leading to the correction factor makes use of only the basic photocell relation given above as Equation 33. Let subscript \( a \) refer to the photocell which measures the total photon rate, \( M_a \), in the beam. Let subscript \( b \) refer to the photocell which measures the photon rate, \( M_b \), through \( A_w \). Equation 33 gives

\[
J_a = S_a M_a, \\
J_b = S_b M_b.
\]
A rearrangement of the terms in the ratio of these currents gives

\[ M_b = (S_a J_b / S_b J_a) M_a. \]  

(37)

This expression relates the total photon rate in the monochromatic beam to the photon rate in the portion of the beam which normally strikes the diamond under test. The photocell current \( J_0 \) measured for each individual decay run is given by

\[ J_0 = S_a M_0. \]

Now \( M_0 \) is the same as \( M_a \) so Equation 37 gives

\[ M_b = (S_a J_b / S_b J_a) J_0 / S_a = C J_0 / S_a \]

where \( C = (S_a J_b / S_b J_a) \), the correction factor. Assuming that \( \phi \) was uniform over the small portion of the beam striking the diamond, one finds that the photon flux density incident on the NESA glass plate directly over the diamond was

\[ \phi_1 = C J_0 / S_a A_w. \]

The desired correction is thus accomplished. In \( C \), the ratio of \( I_b \) to \( I_a \) was obtained in the auxiliary experiment and the ratio of the sensitivities was obtained from a calibration procedure identical to that described in subsection 3. The photon flux density entering the diamond is, by Equation 35

\[ \phi = (t)(1-r) C J_0 / A_w S_a = F J_0 \]  

(38)

where \( F = t(1-r)C/A_w S_a \) is the overall conversion factor relating \( J_0 \) to \( \phi \).
The ratio of $I_b$ to $I_a$ in the conversion factor $C$ was found experimentally to vary in a smooth manner with intensity for each wavelength from each primary source, so a smooth curve was drawn through the observations for each wavelength. The ratio corresponding to the experimental conditions of the individual internal field decay runs could be obtained from the smooth curve. As a check, for many points the actual experimental conditions were reproduced for a current ratio determination. In place of a display of the ten current ratio curves, the less space consuming tables of the correction factor for the experimental conditions of each internal field decay run are given for both diamonds. The values for D1 runs are given in Table 11 in subsection 4 of this appendix. The values for D4 runs are given in Table 12 in that same subsection.

3. Photocell sensitivity calibration

The calibration of the photocells used in the intensity measurement was accomplished by direct comparison of the currents from the experimental photocells with the currents from calibrated photocells when the same M was incident on each. The "standard" photocells were calibrated by the National Bureau of Standards for relative spectral sensitivity at equal values of incident energy.

a. Theory of the calibration If the same photon rate is incident on each of two photocells, the photocell
currents observed are

\[
J_1 = S_1 \text{M} \\
J_2 = S_2 \text{M}.
\]

The ratio can be rearranged to give

\[
S_1 = (J_1/J_2) \cdot S_2 .
\]  

(39)

But if one of these photocells (subscript 2) has already been calibrated by the National Bureau of Standards, then a measurement of the current ratio under the stated conditions allows the determination of the photocell sensitivity of the other photocell. It should be noted that the calibration by the National Bureau of Standards is only for relative spectral sensitivity at equal values of incident energy and is not an absolute calibration. Now, \( S_2 = s_2 G_2 \) where \( s_2 \) is the relative spectral sensitivity which is a function of photon energy, and \( G_2 \) is the absolute sensitivity at some specific photon energy (usually the photon energy corresponding to the maximum relative spectral sensitivity). \( G_2 \) is a constant for any one photocell. The values of \( s_2 \) are obtained from the calibration data supplied by the National Bureau of Standards, but the value of \( G_2 \) is unknown. The calibration of photocell 1 is then in terms of the unknown constant \( G_2 \). The calibration amounts to a calibration of the relative spectral sensitivity of photocell 1, not a calibration of the absolute sensitivity.

b. Apparatus  
The apparatus consisted of the
monochromator, the indexed mirror assembly used in the main experiment, the photocells, a battery pack, and an RCA Microammeter Model WV84A. The photocells, mirror assembly and battery pack were housed in a large box called the calibration box.

The indexed mirror assembly has been described in Section II-B. In this calibration apparatus one photocell was situated at each index position, the center of each tube being one and 5/8 inches from the center of the mirror. Alignment mechanisms were provided to insure that the monochromatic beam which was directed by the mirror into the window of standard photocell would fall entirely in the window of the experimental photocell when the mirror was turned. The monochromator and dc microammeter have been described in Section II-B. The calibration box was attached directly to the monochromator so no stray light could enter the box. As a precaution, the interior of the box was painted with a flat black lacquer to minimize reflection.

c. Procedure The procedure was very simple. The monochromator was set at one of the wavelengths used in the main experiment, and the light intensity was adjusted to a level which produced a reasonable photocell current from the standard photocell. When the photocell current was recorded, the mirror was rotated to cause the same light beam to be incident on the experimental photocell and the resulting current was again recorded. At any one wavelength and
intensity this pair of current measurements was repeated four or five times. This basic procedure was applied at all desired wavelengths and at several intensities for some wavelengths. At some wavelengths (578 millimicrons and 546 millimicrons), all four photocells (the two 929 tubes and the two 925 tubes) are sufficiently sensitive to produce observable currents. In these cases currents from all four tubes were recorded with the same photon rate incident on each.

d. Analysis and results

The sensitivity of the experimental photocell was obtained from Equation 39. The standard sensitivity was obtained from the smooth curve drawn through the calibration data supplied by the National Bureau of Standards. Table 9 is the tabulation of the spectral sensitivities of these photocells. For completeness, the spectral sensitivities of the standards are also included.

The knowledge of the currents from all four photocells when they are illuminated by the same light beam allows the determination of the absolute sensitivity of the 925 photocell relative to that of the 929 photocell. The ratio of these absolute sensitivities is just the ratio of the observed photocell currents. From the knowledge of this ratio and the relative sensitivities of the two photocells, the ratio of the absolute sensitivities of the 925 and 929 experimental photocells at their peak responses was found to be 0.105 ± 0.005. With this knowledge available, only the absolute sensitivity of the 929 photocell had to be known.
### Table 9. Relative spectral sensitivities

<table>
<thead>
<tr>
<th>Wavelength millimicrons</th>
<th>Spectral sensitivity of 929-3&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Spectral sensitivity of 929-2&lt;sup&gt;a&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>350</td>
<td>6.89</td>
<td>5.77</td>
</tr>
<tr>
<td>365</td>
<td>7.09</td>
<td>6.24</td>
</tr>
<tr>
<td>404</td>
<td>6.73</td>
<td>5.86</td>
</tr>
<tr>
<td>435</td>
<td>6.20</td>
<td>5.44</td>
</tr>
<tr>
<td>450</td>
<td>5.86</td>
<td>4.98</td>
</tr>
<tr>
<td>546</td>
<td>2.63</td>
<td>2.44</td>
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<tr>
<td>578</td>
<td>1.29</td>
<td>1.29</td>
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<tr>
<td>595</td>
<td>0.59</td>
<td>0.60</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Spectral sensitivity&lt;sup&gt;b&lt;/sup&gt; of 925-1&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Spectral sensitivity&lt;sup&gt;b&lt;/sup&gt; of 925-2&lt;sup&gt;a&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>546</td>
<td>1.58</td>
<td>1.59</td>
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<tr>
<td>578</td>
<td>1.90</td>
<td>1.93</td>
</tr>
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<td>595</td>
<td>2.02</td>
<td>2.27</td>
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<tr>
<td>630</td>
<td>2.23</td>
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<td>670</td>
<td>2.57</td>
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<td>750</td>
<td>3.55</td>
<td>3.59</td>
</tr>
<tr>
<td>825</td>
<td>4.10</td>
<td>3.78</td>
</tr>
</tbody>
</table>

<sup>a</sup>Standard 929 phototube = 929-3  
Experimental 929 phototube = 929-2  
Standard 925 phototube = 925-1  
Experimental 925 phototube = 925-2.

<sup>b</sup>925 sensitivities on different absolute scale than 929's.
to obtain the absolute sensitivities of both photocells throughout the range of wavelengths used in the experiment.

4. Final results for the conversion to photon flux density

The formula for the conversion of observed photocell current to photon flux density has been given as Equation 38. Knowledge of the transmittance of the NESA glass plate, the reflectance of the diamond and the absolute sensitivity of the 929 photocell are required to complete the determination of the conversion factor. The transmittance of the NESA glass plate was determined by one of the service groups in the Ames Laboratory. The reflectance of the diamond was determined from the data given by Peter (3) on the variation of the refractive index with wavelength by use of Equation 36. This correction for reflection is only a very rough one because the diamond surface was neither plane nor polished. The results of the experiment are, fortunately, not much affected by its presence or absence. The absolute sensitivity of the 929 photocell was taken to be that given in the RCA Tube Manual. This manual value was probably within 50 per cent of the absolute sensitivity of the 929 photocell used in the experiment. Only the absolute value of $\phi$ is affected by this sensitivity. The relative values at the various photon energies are unaffected by the uncertainty. The ratio $t(1-r)/A_w S_a$ is given in Table 10 for each photon energy. The product of this ratio with the correction factor
C given in the third column in Tables 11 and 12 gives the conversion factor $F$ tabulated in the fourth column. The photon flux density incident on the diamond in the run is $F J_0$.

Table 10. Values of $t(1-r)/A_w S_a$ at the photon energies used in this experiment

<table>
<thead>
<tr>
<th>Photon Energy ($\text{ev}$)</th>
<th>$t(1-r)/(A_w S_a)$ ($\text{cm}^{-2} \text{sec}^{-1} \mu \text{amp}^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.54</td>
<td>$0.116 \times 10^{15}$</td>
</tr>
<tr>
<td>3.40</td>
<td>0.116</td>
</tr>
<tr>
<td>3.07</td>
<td>0.146</td>
</tr>
<tr>
<td>2.85</td>
<td>0.173</td>
</tr>
<tr>
<td>2.75</td>
<td>0.197</td>
</tr>
<tr>
<td>2.27</td>
<td>0.500</td>
</tr>
<tr>
<td>2.15</td>
<td>1.01</td>
</tr>
<tr>
<td>2.08</td>
<td>7.06</td>
</tr>
<tr>
<td>1.97</td>
<td>6.71</td>
</tr>
<tr>
<td>1.85</td>
<td>6.17</td>
</tr>
<tr>
<td>1.65</td>
<td>5.15</td>
</tr>
</tbody>
</table>

5. Error analysis

The analysis of the errors associated with the conversion from $J_0$ to $\varnothing$ can be divided into three subanalyses. The first subanalysis is for those errors which affect the determination of the slope of the intensity effect plots. The second subanalysis is for those errors which affect the relative values of $\varnothing$ for different photon energies. The final
Table 11. Correction and conversion factors for D1 in Apparatus II

<table>
<thead>
<tr>
<th>Photon energy (ev)</th>
<th>Run no.</th>
<th>Correction factor, C</th>
<th>Conversion factor, F (cm^{-2} sec^{-1} \mu amp^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.54</td>
<td>1-124</td>
<td>0.198</td>
<td>0.229 x 10^{14}</td>
</tr>
<tr>
<td></td>
<td>1-120</td>
<td>0.161</td>
<td>0.186</td>
</tr>
<tr>
<td>3.40</td>
<td>1-112</td>
<td>0.290</td>
<td>0.338</td>
</tr>
<tr>
<td></td>
<td>1-114</td>
<td>0.278</td>
<td>0.324</td>
</tr>
<tr>
<td>3.07</td>
<td>1-118</td>
<td>0.406</td>
<td>0.591</td>
</tr>
<tr>
<td></td>
<td>1-116</td>
<td>0.356</td>
<td>0.519</td>
</tr>
<tr>
<td>2.85</td>
<td>1-132</td>
<td>0.524</td>
<td>0.905</td>
</tr>
<tr>
<td></td>
<td>1-123</td>
<td>0.148</td>
<td>0.256</td>
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<tr>
<td></td>
<td>1-111</td>
<td>0.359</td>
<td>0.620</td>
</tr>
<tr>
<td></td>
<td>1-110</td>
<td>0.515</td>
<td>0.544</td>
</tr>
<tr>
<td>2.75</td>
<td>1-122</td>
<td>0.144</td>
<td>0.284</td>
</tr>
<tr>
<td></td>
<td>1-121</td>
<td>0.167</td>
<td>0.329</td>
</tr>
<tr>
<td>2.27</td>
<td>1-115</td>
<td>0.261</td>
<td>1.30</td>
</tr>
<tr>
<td></td>
<td>1-108</td>
<td>0.218</td>
<td>1.09</td>
</tr>
<tr>
<td></td>
<td>1-119</td>
<td>0.182</td>
<td>0.929</td>
</tr>
<tr>
<td></td>
<td>1-135</td>
<td>0.170</td>
<td>0.849</td>
</tr>
<tr>
<td></td>
<td>1-107</td>
<td>0.170</td>
<td>0.849</td>
</tr>
<tr>
<td>2.15</td>
<td>1-117</td>
<td>0.160</td>
<td>1.63</td>
</tr>
<tr>
<td></td>
<td>1-109</td>
<td>0.160</td>
<td>1.63</td>
</tr>
<tr>
<td></td>
<td>1-113</td>
<td>0.153</td>
<td>1.56</td>
</tr>
<tr>
<td>2.08</td>
<td>1-131</td>
<td>0.147</td>
<td>10.4</td>
</tr>
<tr>
<td>1.97</td>
<td>1-130</td>
<td>0.147</td>
<td>9.87</td>
</tr>
<tr>
<td></td>
<td>1-126</td>
<td>0.147</td>
<td>9.87</td>
</tr>
<tr>
<td>1.85</td>
<td>1-129</td>
<td>0.145</td>
<td>8.95</td>
</tr>
<tr>
<td></td>
<td>1-127a</td>
<td>0.145</td>
<td>8.95</td>
</tr>
<tr>
<td>1.65</td>
<td>1-128</td>
<td>0.138</td>
<td>7.11</td>
</tr>
<tr>
<td></td>
<td>1-125</td>
<td>0.138</td>
<td>7.11</td>
</tr>
</tbody>
</table>
### Table 12. Correction and conversion factors for D4 in Apparatus II

<table>
<thead>
<tr>
<th>Photon energy (eV)</th>
<th>Run no.</th>
<th>Correction factor, C</th>
<th>Conversion factor, F (cm⁻² sec⁻¹ μamp⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.54</td>
<td>4-42</td>
<td>0.155</td>
<td>0.179 x 10¹⁴</td>
</tr>
<tr>
<td></td>
<td>4-52</td>
<td>0.142</td>
<td>0.184</td>
</tr>
<tr>
<td>3.40</td>
<td>4-37</td>
<td>0.259</td>
<td>0.302</td>
</tr>
<tr>
<td></td>
<td>4-40</td>
<td>0.247</td>
<td>0.288</td>
</tr>
<tr>
<td></td>
<td>4-55</td>
<td>0.245</td>
<td>0.285</td>
</tr>
<tr>
<td>3.07</td>
<td>4-54</td>
<td>0.215</td>
<td>0.313</td>
</tr>
<tr>
<td></td>
<td>4-55</td>
<td>0.146</td>
<td>0.213</td>
</tr>
<tr>
<td></td>
<td>4-53</td>
<td>0.145</td>
<td>0.213</td>
</tr>
<tr>
<td></td>
<td>4-34</td>
<td>0.218</td>
<td>0.318</td>
</tr>
<tr>
<td></td>
<td>4-39</td>
<td>0.215</td>
<td>0.313</td>
</tr>
<tr>
<td></td>
<td>4-38</td>
<td>0.189</td>
<td>0.275</td>
</tr>
<tr>
<td></td>
<td>4-33</td>
<td>0.197</td>
<td>0.287</td>
</tr>
<tr>
<td>2.85</td>
<td>4-41</td>
<td>0.236</td>
<td>0.408</td>
</tr>
<tr>
<td></td>
<td>4-46</td>
<td>0.222</td>
<td>0.383</td>
</tr>
<tr>
<td></td>
<td>4-27</td>
<td>0.202</td>
<td>0.349</td>
</tr>
<tr>
<td></td>
<td>4-36</td>
<td>0.174</td>
<td>0.300</td>
</tr>
<tr>
<td></td>
<td>4-26</td>
<td>0.163</td>
<td>0.282</td>
</tr>
<tr>
<td>2.27</td>
<td>4-28a</td>
<td>0.249</td>
<td>1.24</td>
</tr>
<tr>
<td></td>
<td>4-28b</td>
<td>0.188</td>
<td>0.939</td>
</tr>
<tr>
<td></td>
<td>4-29a</td>
<td>0.166</td>
<td>0.829</td>
</tr>
<tr>
<td></td>
<td>4-28c</td>
<td>0.158</td>
<td>0.789</td>
</tr>
<tr>
<td></td>
<td>4-30</td>
<td>0.154</td>
<td>0.769</td>
</tr>
<tr>
<td></td>
<td>4-31</td>
<td>0.154</td>
<td>0.769</td>
</tr>
<tr>
<td></td>
<td>4-29b</td>
<td>0.149</td>
<td>0.744</td>
</tr>
<tr>
<td>2.15</td>
<td>4-43a</td>
<td>0.156</td>
<td>1.58</td>
</tr>
<tr>
<td></td>
<td>4-43b</td>
<td>0.148</td>
<td>1.50</td>
</tr>
<tr>
<td></td>
<td>4-44</td>
<td>0.144</td>
<td>1.46</td>
</tr>
<tr>
<td>1.97</td>
<td>4-45a</td>
<td>0.147</td>
<td>9.87</td>
</tr>
<tr>
<td></td>
<td>4-46</td>
<td>0.147</td>
<td>9.87</td>
</tr>
<tr>
<td>1.85</td>
<td>4-45b</td>
<td>0.145</td>
<td>8.95</td>
</tr>
<tr>
<td></td>
<td>4-47</td>
<td>0.145</td>
<td>8.95</td>
</tr>
<tr>
<td>1.65</td>
<td>4-45c</td>
<td>0.138</td>
<td>7.11</td>
</tr>
</tbody>
</table>
subanalysis is for those errors affecting the absolute value of the $\phi$.

a. **Analysis of errors which affect the intensity effect plots**  
Only the correction factor, $C$, affects the slope of the intensity effect plots. According to the usual methods, the fractional standard error of the $C$ is equal to the square root of the sum of the squares of the fractional standard error of the ratio of $S_a/S_0$ and the fractional standard error of the ratio $J_b/J_a$. Each of these last mentioned fractional standard errors are estimated to be 0.06 so the fractional standard error in $C$ is about 0.08.

b. **Analysis of errors which affect the relative values of the photon-induced decay constants**  
Some of the remaining quantities in the conversion factor may be divided into two factors, one of which varies with photon energy, and one of which is just an absolute multiplier. The transmittance $t$ may be assumed to be $t = mT$ where $m$ is a factor giving the relative spectral transmittance and $T$ is an absolute multiplier. In the same manner,

$$1-r = pP$$

where $p$ is the relative spectral transmittance of the diamond surface and $P$ is the absolute multiplier. Also the photocell sensitivity

$$S_a = s_aG$$

where $s_a$ is the relative spectral sensitivity and $G$ is the absolute multiplier. With the substitution of these
quantities,
\[ \phi = \left( \frac{mT}{pF} \frac{\alpha s_a}{A_w} G \right) \psi J_o = \left( \frac{mp}{S_a} \right) \left( \frac{TP}{A_w G} \right) \psi J_o. \]

The first parenthesis contains the terms contributing to the variation of \( \phi \) with photon energy. The second parenthesis is the total absolute multiplier. The fractional standard error of the relative photon flux density factor is the square root of the sum of the squares of the fractional standard errors of \( m, p, \) and \( s_a \). The fractional standard errors of \( m \) and \( p \) are estimated to be 0.02 while a reasonable estimate for \( s_a \) based on an analysis of the errors in the calibration procedure is 0.05. The fractional standard error of the relative photon flux density factor is then roughly 0.06.

The error in the absolute photon flux density factor is dominated by the uncertainty in the absolute sensitivity of the photocells. A reasonable estimate of the fractional standard deviation of this absolute photon flux density factor is 0.60.

E. Appendix E: Intensity Effect Plots

The intensity effect plots described in Section V-C are given on the next few pages. Figures 56 through 64 are the intensity effect plots for D1 in Apparatus II. Note that the ordinate and abscissa scales are different for the different plots. Figures 65 through 71 are the intensity effect plots for D4 in Apparatus II.
Figure 58. Intensity effect plot for 350 millimicrons for DI.
Figure 57. Intensity effect plot for 365 millimicrons for D1.
Figure 58. Intensity effect plot for 404 millimicrons for DI.
Figure 59. Intensity effect plot for 450 millimicrons for D1.
Figure 60. Intensity effect plot for 546 millimicrons for D1.
Figure 61. Intensity effect plot for 578 millimicrons for D1.
Figure 62. Intensity effect plot for 630 millimicrons for D1.
Figure 63. Intensity effect plot for 670 millimicrons for Dl.
Figure 64. Intensity effect plot for 750 millimicrons for DI.
Figure 65. Intensity effect plot for 350 millimicron light for D4.
Figure 66. Intensity effect plot for 365 millimicron light for D4.
Figure 67. Intensity effect plot for 435 millimicron light for D4.
Figure 68. Intensity effect plot for 546 millimicron light for D4.
Figure 69. Intensity effect plot for 578 millimicron light for D4.
Figure 70. Intensity effect plot for 630 millimicron light for D4.
Figure 71. Intensity effect plot for 670 millimicron light for D₄.
F. Appendix F: Auxiliary Experiments

Two auxiliary experiments will be discussed in this appendix. The first was a brief investigation of the phenomenon of dark polarization discovered during the early work on the main experiment and observed throughout the experiment. The second experiment, the observation of the growth of the internal field during a period of application of an applied field and gamma radiation to the diamond, was undertaken to check on the validity of the assumption that the field effective in causing the drift of liberated electrons and holes is the difference between the applied field and the internal field.

1. Dark polarization

Dark polarization is the name given to the internal electric field which appears in a diamond upon the application of an electric field in the absence of ionizing radiation of any kind (light or nuclear radiation). Several days were spent in a brief investigation of the properties of this phenomenon in both D1 and D4. The internal field was found to build up within one minute to about half the value of the maximum $E_1$ obtained after an application of an applied field and gamma rays for an hour. This dark polarization persisted upon removal of the applied field in the same manner that the normal $E_1$ persists. The dark polarization decayed in the dark and also when light was applied. The decay constants
were about two times larger for the dark polarization decay than for the normal internal field decay. This factor of two was observed for the dark decay and for two different wavelengths (546 and 578 millimicrons) utilized in the photon-induced decay.

After this brief investigation was completed, it was found that Pearlstein (50) had observed dark polarization in diamond previously. He was able to destroy the capability of the diamond to polarize in the dark by heating the diamond to 400° C. and subsequently keeping it in the dark and away from nuclear radiation. Incidence of exciting radiation caused the diamond to return to a state in which it could polarize in the dark. These observations appear to be in accord with observations of the dark polarization obtained in many substances by Kallmann and Rosenberg (48).

The dark polarization appears to be an internal field generated by a spatial displacement of trapped charges of opposite sign. The excitation mechanism is still a matter of conjecture but occupation of trapping levels appears to be a necessary condition for the phenomenon, so one suspects that the mobile charge carriers are excited from traps. Further investigation of this phenomenon in diamond would be useful.

2. Growth of the internal field during the applied field counting period

During the time an electric field is applied to a
diamond and gamma radiation is incident upon it, $E_1$ is supposed to be increasing as more electrons and holes are separated and trapped. A check on this assumed mechanism was afforded by the simple process of observing $R_1$ at various times during the total applied field counting period. This auxiliary experiment was performed on both diamonds. For each diamond the growth of the dark polarization described in Subsection 1 of this appendix was investigated before the gamma radiation was applied with the electric field.

a. Apparatus and procedure The apparatus used in this investigation was just that used in the main experiment. The procedure was as follows. The high voltage (480 volts for D4 and 510 volts for D1) was applied to the diamond with the gamma source in its shielded position. At the end of one minute, $R_1$ was observed for thirty seconds. The transition to the internal field counting condition was made by performing the following operations in rapid succession: switching the transparent electrode to ground from the high potential, moving the gamma source to its "count" position, and activating the scaler. The resulting $R_1$ was a measure of $E_1$ or dark polarization. At the end of thirty seconds the scaling action was stopped and the gamma source removed to its shielded position. After $R_1$ was recorded, the high voltage was applied again, this time for three minutes, after which $R_1$ was observed by the same procedure described above.
After another application of the applied field alone and the subsequent observation of \( R_i \), the high voltage was applied and gamma radiation was incident at the same time. The \( R_a \)'s were observed during this application. The decay of \( R_a \) indicated that an internal field was being produced in the diamond. At the various times plotted on the graphs of the results, \( R_i \) was observed to check on the magnitude of \( E_i \). The transition from the applied field conditions to the internal field conditions was made by the same procedure used in the main experiment and described in Section III-C-1.

b. Results and discussion The results of this auxiliary experiment are plotted in Figures 72 and 73 for D1 and D4 respectively. The applied field counting rates are noted as triangles in the figures and the internal field counting rates as circles. Smooth curves have been drawn through the experimental data in each figure to denote the variation of counting rates expected from the experimental data. The periods of application of applied field alone and applied field with gamma radiation are given by the horizontal lines near the abscissa in each figure. The applied field was not present, of course, during the observation periods for \( R_i \) even though these lines are shown solid (for ease in drafting) throughout the two periods.

For D1, Figure 72, the dark polarization appears to have grown almost to its full value in one minute. Successive applications of the high voltage in the absence of
Figure 72. Growth of internal field counting rate for Dl.
Figure 73. Growth of internal field counting rate for D4.
gamma radiation caused the dark polarization to increase only slightly. Upon application of the high voltage with the gamma rays at the ten minute mark, \( R_1 \) increased quite rapidly at first and then more slowly with time. The applied field counting rate demonstrated a peculiar behavior. An initial decay was observed with each application of the high voltage and gamma radiation. This decay is ascribed to the regrowth of a portion of the internal field which decayed between applications of the high voltage while \( R_1 \) was being observed. (The internal field counting rate was observed to decrease during its observation period. The counting rates shown in the figure are average values for the thirty second counting period.) After the initial decay, \( R_a \) decayed only slowly with time. The rate of this slow decay of \( R_a \) appears to be slower than the rate of increase of the \( R_1 \). This fact is qualitatively understandable in terms of \( E_e \) and \( E_1 \) associated with the two counting rates. According to the Equation 13, 
\[
E_e = E_a - E_1.
\]
The decay of \( R_a \) is caused by the decay of \( E_e \) which in turn is a result of the growth of the \( E_1 \). The applied field counting rate, \( R_a \), then decreases as \( R_1 \) increases with time. Figures 54 and 55 may be used to convert the counting rates to electric fields. For D1, the decrease in \( R_a \) from about 79 units per minute to 72 units per minute (Figure 72) is caused by a change in \( E_e \) of about 85 (x 20) volts cm\(^{-1}\). The internal field during this same period of
time has grown about 75 volts corresponding to a change of counting rate from 42 to 58 units per minute. The agreement is rather good considering the experimental difficulties involved.

The same general behavior is observed with D4, whose counting rate variations are shown in Figure 73. This diamond displays only a slow variation of counting rate with time. Therefore, no complications arise in the determination of meaningful counting rates as they did with Diamond One. The dark polarization is built up to its full value within one minute of the application of a high voltage. When both gamma rays and the high voltage are applied to the diamond, $R_i$ begins to increase rapidly but in a short time its rate of growth decreases to about a constant value. While $R_i$ grows $R_a$ steadily decreases. The rate of growth is greater than the rate of decrease. But, when the counting rates are transformed to fields by use of Figure 55 in Appendix C, $E_o$ is found to have decreased about 340 (x 14.5) volts per centimeter, while $E_i$ has increased only about 100 (x 14.5) volts per centimeter in the same period. This discrepancy is unresolved.