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The luminescence response of zinc-silicate:manganese to bombardment by ions with energies in the kilo electron volt range.

Donald J. Bradley
University of Windsor

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THE LUMINESCENCE RESPONSE OF Zn$_2$SiO$_4$:Mn TO BOMBDMENT
BY IONS WITH ENERGIES IN THE KILO ELECTRON VOLT RANGE

BY
Donald J. Bradley

A Thesis
Submitted to the Faculty of Graduate Studies through the Department
of Physics in Partial Fulfillment of the Requirements for
the Degree of Master of Science at the
University of Windsor.

Windsor, Ontario
1965
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APPROVED

John Huschilt
Dr. J. Huschilt

David Robinson
Dr. D. Robinson

Dr. A. van Wijngaarden (supervisor)

110768
ABSTRACT

$\text{Zn}_2\text{SiO}_4:\text{Mn}$ phosphor was bombarded with H, Li, Na, K, Rb, Cs ions in the energy range 5 to 70 keV. The energy dependence of the intensity of the resulting luminescence is compared to a theoretical calculation of the amount of energy that bombarding ions impart to electrons in the target material.

Good agreement between theory and experiment is obtained.
ACKNOWLEDGEMENTS

I should like to express my gratitude to Dr. Arie van Wijngaarden for his aid and guidance during the course of this work.

I gratefully acknowledge the financial assistance which was extended to me, in the form of a bursary, by the Province of Ontario.
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CHAPTER 1
Introduction

1. Survey of the Literature

The luminescence response of phosphors under low energy ion bombardment has mainly been studied by Eve and Duckworth (1958). They bombarded samples of ZnSi:Ag and Zn$_2$SiO$_4$:Mn with positive ions such as H$^+$, Li$^+$, Na$^{23+}$, K$^{39+}$, and Rb$^{85+}$ and observed the luminescence response as a function of ion energy for energies between 5 and 30 keV. In this range, the luminous efficiency decreased rapidly as the mass of the projectile increased. The observed light output, $L$, per unit ion current, in the 4-25 keV energy range studied, was presented in the form

$$L \propto (E - E_0)^n$$  \hfill (1)

where $E$ is the energy of the incident ion (projectile). The so-called threshold energy, $E_0$, is of the order of a few keV for ZnSi:Ag as target material and is somewhat less for Zn$_2$SiO$_4$:Mn. For example, the luminous response of ZnSi:Ag to H$^+$ ions in the energy range 7-22 keV satisfied the relation

$$L \propto (E - 3.5 \text{ keV})^{1.11}$$  \hfill (2)

Eve and Duckworth did not present data on the luminescence response of Zn$_2$SiO$_4$:Mn to H$^+$ ion excitation.

In the analysis of their results, Eve and Duckworth assumed that the stopping power of the phosphors, for the various projectiles,
was independent of ion energy. This assumption was based mainly on the theoretical work of Bohr (1918) and of Nielsen (1956), who predicted that the stopping power of a target material for a heavy atomic projectile whose velocity is smaller than the velocity of the electron in the first Bohr orbit in hydrogen is approximately constant. However, it has been recently shown (van Wijngaarden and Duckworth, 1962; (Ormrod and Duckworth, 1963) that, in the keV range, the stopping power is not constant, but increases with energy. Their results are in good agreement with theory (Lindhard and Scharff, 1961). (See chapter I section (2)). Using protons as projectiles and $Zn_2SiO_4$ as target material, van Wijngaarden (unpublished experiment) obtained a linear relationship between the light output per unit ion current and the energy of the projectiles in the energy range 5-70 keV. He also observed a threshold energy of about 0.8 keV. These data are shown in Figure 1. In addition to this, by using a layer of $Zn_2SiO_4$ about 0.2 mm thick deposited on glass, he observed that the light output coming from the opposite surface of the phosphor to that being bombarded had the same energy dependence as the light coming from the bombarded surface. In this way, he ascertained that the phosphor is transparent to its own luminescence. This means that the energy dependence of the observed light output does not vary with the length of the light path in the phosphor. Therefore, the light detected by the photomultiplier is proportional to the total light produced along the entire path of the projectile through the phosphor.

In his experiment, the spectral distribution of the luminescence was not investigated. However, it was observed to be a bright green, about 5500 Å. $Zn_2SiO_4$ is used for the green colour in colour television receivers.
Figure 1. A plot of $I$ versus $E$ for protons bombarding a sample of $\text{Zn}_2\text{SiO}_4:\text{Mn}^+$, in the energy range 8 - 73 keV.
2. The Mechanism of Energy Loss

A low speed atomic particle, in travelling through a medium, may interact with the electrons in it. The electrons may be ejected from their parent atoms or may make transitions between discrete states. Interactions with the positive charges of the nucleus may also occur. These elastic collisions, involving nuclei, are commonly called nuclear collisions. They cause a recoil of the affected nuclei together with their orbiting electrons.

Thus the energy, \( dE \), a projectile loses in moving a small distance, \( dR \), through a stopping medium may be represented as

\[
\frac{dE}{dR} = \frac{dE_e}{dR} + \frac{dE_n}{dR}
\]

where \( dE_e \) is the energy lost to the electrons and \( dE_n \) is the energy lost to the nuclei in the target material. The stopping power, \( -\frac{dE}{dR} \), the negative of the differential energy loss, \( \frac{dE}{dR} \), is related to the total stopping cross section, \( S \), per atom of the stopping medium as

\[
\frac{dE}{dR} = NS
\]

where \( N \) is the number of stopping atoms per unit volume. The total stopping cross section consists of the electronic component, \( S_e \), and the nuclear component, \( S_n \):

\[
S = S_e + S_n
\]

From equations (3), (4), and (5) it follows that
The electronic component, $S_e$, of the total stopping cross section, $S$, varies as the velocity of the projectile (Lindhard and Scharff 1961):

$$S_e \propto V$$  \hspace{1cm} (7)

$S_h$ was first discussed by Bohr (1918) and various approximations of it, for various energy ranges, have been recently proposed by Lindhard and Scharff (1961).

Lindhard's presentation includes the variables (Lindhard et al. 1963)

$$\rho = \frac{\text{N} M M_2}{4} \frac{a^2}{(M_1 + M_2)^2}$$  \hspace{1cm} (8)

and

$$\epsilon = \frac{E a M_2}{Z_1 Z_2 e^2 (M_1 + M_2)}$$  \hspace{1cm} (9)

as dimensionless measures of range, $R$, and energy, $E$, respectively. Here $M_1$ and $Z_1$ are the mass and atomic number of the projectile while $M_2$ and $Z_2$ are the mass and atomic number of the atom in the stopping medium respectively; $e$ is the electronic charge, and $a$ is a screening parameter given by

$$a = \frac{a_0 \times 0.8853}{\sqrt[3]{Z_1^{2/3} + Z_2^{2/3}}}$$

where $a_0$ is the Bohr radius. In these expressions, the quantities involved are expressed in electrostatic units.
The electronic component of the energy loss is given by

\[ \left( \frac{d\varepsilon}{d\rho} \right)_e = k \varepsilon^{1/2} \]  

(10)

The constant \( k \) is given by

\[ k = Z_1^{1/6} \frac{0.0793 Z_1^{1/2} Z_2^{1/2}(M_1 + M_2)^{3/2}}{(Z_1^{2/3} + Z_2^{2/3})^{3/4} M_1^{3/2} M_2^{1/2}} \]

Lindhard and Scharff's plot of the differential energy loss to nuclei, \( \left( \frac{d\varepsilon}{d\rho} \right)_n \), as a function of \( \varepsilon^{1/2} \) is shown in Figure 2. In their publication, Lindhard and Scharff did not present an analytic function for this curve.

3. The Luminescence Response to Ion Bombardment

The energy, \( dE_h \), lost by the projectiles in nuclear collisions will cause atomic displacements. Most of this energy will be dissipated as heat. Actually, the recoiling atoms will also cause electronic excitation in the phosphor. However, this indirect excitation of electrons will be of much less importance than the direct excitation of electrons by the projectile. The reason for this is that collisions in which only a small amount of energy is lost by the projectile occur much more frequently (Bohr, 1918) than the more violent collisions in which the particles involved may recoil with a velocity comparable to that of the projectile. Thus, it appears that most of the electronic excitation in the phosphor should be attributed to direct interaction between the projectile and the electrons in the phosphor.
Figure 2. The nuclear component, $\left( \frac{d\varepsilon}{d\rho} \right)_n$, of the differential energy loss as a function of $\varepsilon^{1/2}$. Solid portion of the curve is due to Lindhard and Scharff.
From Equation (6), the total amount of energy transferred to electrons along an element, \( dR \), of the trajectory of the projectile through the phosphor is seen to be

\[
d\bar{E}e = N\bar{E}dR
\]

Let \( dL \) be the intensity of the light originating along \( dR \). The intensity of the luminescence is proportional to the number of electrons which are excited into the energy states from which a radiative transition can occur. In other words, the intensity of the luminescence is a function of the amount of energy transferred to electrons. Let us assume that, for a given projectile,

\[
dL = Cd\bar{E}e
\]

where \( C \) is a constant. In the next section, an attempt will be made to justify this assumption on the basis of experimental evidence.

Using Equation (3), Equation (12) can be rewritten as follows:

\[
dL = C \left| \frac{\left( \frac{d\bar{E}}{dR} \right)_e}{\left( \frac{d\bar{E}}{dR} \right)_e + \left( \frac{d\bar{E}}{dR} \right)_n} \right| d\bar{E}
\]

Thus, the total light intensity, \( L \), produced along the entire trajectory, \( R \), of a projectile entering the phosphor with an initial energy \( E \) and coming to rest inside the phosphor is

\[
L(E) = C \left| \int_0^E \frac{(d\bar{E})_e}{(d\bar{E})_e + (d\bar{E})_n} d\bar{E} \right| 
\]

which, on substitution of equation (6) reduces to
\[ L(E) = C \left| \int_0^E \frac{S_e}{S_e + S_n} dE \right| \]  

Substitution of equations (8) and (9) into (13) yields

\[ L(E) = C \frac{Z_1 Z_2 e^{2(M_1 + M_2)}}{a M_2} \left| \int_0^\epsilon_u \frac{(d\epsilon)(d\rho_e)}{(d\rho_e) + (d\rho)_n} d\epsilon \right| \]

where the upper limit \( \epsilon_u \) is given by

\[ \epsilon_u = \frac{E a M_2}{Z_1 Z_2 e^{2(M_1 + M_2)}} \]  

Equation (15) can be integrated numerically using Figure 2. Since it may be easily shown that \( (d\epsilon)/(d\rho)_n \to 0 \) as \( \epsilon \to 0 \), Lindhard’s curve in Figure 2 is extrapolated to zero as shown by the dotted portion of the curve. There is, of course, some latitude in this extrapolation, but the error introduced will be negligible if the range of integration is appreciably larger than the range of the extrapolation.

For a target material consisting of a mixture of different atomic species, an L value will be calculated separately for each of the constituents. Thus if, for example, the target material is Zn\(_2\)SiO\(_4\), the L value should be proportional to the sum of twice the L value for Zn, plus that of Si, plus four times the L value of O.

The results of these calculations are plotted in Figure 3 for various bombarding ions. In this figure, the value of \( C \) is taken to be
Figure 3. Theoretical L values versus energy for various projectiles bombarding $Zn_2SiO_4:^{131}I_3$. 

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the same for all of the projectiles. Further comments on the value of C are made in the next section and in Chapter IV.

4. Interpretation of the Hydrogen Data on the Basis of Theory

The luminescence response of Zn$_2$SiO$_4$:Mn to proton bombardment as measured by van Wijngaarden (unpublished experiment) is shown in Figure 1. The solid line in Figure 1 is a plot of the energy lost to electrons versus the energy of the impinging protons. The curve has been obtained by the numerical integration of Equation (15). The slope of the solid line has been adjusted to provide a comparison between theory and results. It is noticed that the solid line is straight down to 8 keV. Below 8 keV, the line bends slightly and passes through the origin. However, the tangent to the straight portion of the line passes through a threshold of about 1 keV, agreeing, within experimental error, with observations.

It is not surprising that, above about 8 keV, the curve in the figure is a straight line because, at these energies, the theory predicts that \( \left( \frac{dE}{dp} \right)_n \ll \left( \frac{dE}{dp} \right)_e \). This is also in agreement with some recent experimental work (van Wijngaarden and Duckworth, 1962). In this case, Equation (15) reduces to

\[
L(E) = \text{Constant} \int_0^E dE
\]

where, now, \( dE = (dE_n + dE_e) = dE_e \). Thus, for protons, it seems indeed true that

\[
dL = CdE_e
\]
where $C$ is independent of the energy of the proton. On the basis of this, $C$ is taken to be independent of the energy in the calculations of the $L$ values for the heavier ions as well.
CHAPTER II

Apparatus

The apparatus is shown schematically in Figure 4. It consists of an ion source E, a high voltage power supply H.V., a magnetic analyser M, an evacuated target chamber in which the ion beam bombards a phosphor, P, and a photomultiplier, P.M.

Source and Acceleration

The source E consists of a heated tungsten filament, F. The filament is coated with the material whose ions are to be used as projectiles. For example, when a beam of sodium ions was required, the filament was coated with NaNO₃. Power to heat the filament is supplied by a 6 volt storage battery, B₁. The rheostat, R₁, controls the filament current. The potential on slit S₁ can be varied from 0 - 15 volts with respect to the filament by means of potentiometer, R₂, and battery B₂. Thus the ions are attracted from the filament and allowed to pass out through slit S₁.

To accelerate the ions in the region between slits S₁ and S₂, the source is connected to the positive output terminal of the high voltage power supply, H.V. (Sorensen, model 2150-5M&D). This power supply is variable from zero to 150 kV.

Magnetic Analysis of the Beam

The magnetic analyser, M, bends the beam by 30°, causing it to pass through slits S₃ and S₄, and into the Faraday cup, C. Slit S₃ is part of the magnetic analyser, allowing only those ions to pass through
Figure 1. Schematic of the apparatus.
whose trajectories have been bent the correct amount by the field $B$.

Slit $S_4$ is kept at a negative potential of 200 volts in order to prevent secondary electrons from escaping from the Faraday cup. An electrometer (Keithly, type 417) is connected to the Faraday cup in order to measure the beam current.

In order to ascertain that the projectiles passing through the analyser are indeed the required ones, the beam is analysed as follows: The magnetic field is kept constant while the accelerating potential is varied. At various potentials, ions of various masses are detected at the Faraday cup. For any two ions, having masses $M_1$ and $M_2$, detected at potentials $V_1$ and $V_2$ respectively, it can be easily shown that

\[
\frac{M_1}{M_2} = \frac{V_2}{V_1}
\]

Thus the ions can be identified by the potential at which they are detected.

The widths of slits $S_2$ and $S_3$ are both equal to 0.012 inches, and the radius of curvature of the central ion beam is 4.0 inches. The observed mass resolution is one part in ten.

The Target and Detection of the Luminescence

By means of a bellows arrangement, the cup can be pulled out of the beam, allowing it to strike the phosphor, $P$. The photomultiplier, P.M. (Philips type 153AVP), indicates the luminescence response of the phosphor to the ion bombardment. A shutter is also provided to prevent light from reaching the photomultiplier when it is desired to measure the photomultiplier dark current. The phosphor can be irradiated with ultraviolet through a quartz window.
In order to measure the photomultiplier current, an electrometer (Keithly model 621) is used. The output of this electrometer drives a recorder (Bausch and Lomb, type V.O.M.-5).

The phosphor sample consists of a thin layer of $\text{Zn}_2\text{SiO}_4:\text{Mn}$ powder deposited out of a liquid suspension onto a flat brass disc. In order to reduce deterioration of the phosphor under ion bombardment, the phosphor sample is moved across the beam while the photomultiplier current is being recorded. A bellows system facilitates this "scanning" of the phosphor.

**Maximum Sensitivity of the Photomultiplier**

The photomultiplier dark current is about $1.4 \times 10^{-8}$ amperes. Noise in the dark current was observed to have an amplitude of about $1.5 \times 10^{-9}$ amperes. Therefore, the lowest luminous intensity detectable corresponds to about $10^{-9}$ amperes. The sensitivity of the photomultiplier at the voltage applied to it in this experiment (1300 volts) is advertised to be 60 amperes per lumen for light with a wavelength of 5500 Å (The approximate wavelength of the light emitted by $\text{Zn}_2\text{SiO}_4:\text{Mn}$). At 5500 Å, one lumen corresponds to $4.63 \times 10^{15}$ photons per second. The sensitivity of the photomultiplier is therefore $7.7 \times 10^{4}$ photons/sec. The area of the sensitized face of the photomultiplier is $4.8 \text{ cm}^2$. The face of the photomultiplier was located 30 cm from the phosphor. Thus only 0.13% of the total number of photons emitted from the phosphor are detected. Therefore, the phosphor has to emit at least $5.9 \times 10^7$ photons per second in order to give a detectable change in the photomultiplier current.
For reasons of lack of sensitivity, the experimental L values could not be obtained at energies much less than 6 keV.

The Vacuum System

The target system consists of a stainless steel chamber evacuated by an oil diffusion pump (Edwards, model 1403) to a pressure of about $5 \times 10^{-7}$ Torr. The source is enclosed by a glass cylinder, about 4 inches in diameter, in order to electrically insulate it from the rest of the system. The ion beam is conducted through the magnetic analyser into the stainless steel chamber by means of 2 inch brass piping. The source and the magnetic analyser are evacuated by an additional oil diffusion pump (Edwards, model E02). Both diffusion pumps are connected to a single rotary mechanical pump (Edwards, model 1SC150B).
CHAPTER III
Observations

1. Variation of Light Output With Ion Current

It was observed, in agreement with Eve and Duckworth, (1958), that, for each energy and for each value of beam current in the ranges of currents and energies investigated, the photomultiplier current varied linearly with the intensity of the beam current striking the phosphor. A typical plot of the photomultiplier current as a function of the beam current is shown in Figure 5, for Li ions of 50.5 keV bombarding our phosphor sample. Beam currents in the range $10^{-11}$ to $10^{-9}$ amperes were used, the lower currents being used for the higher energies and lighter projectiles. At energies below 5 keV it was sometimes impossible to obtain beam currents as high as $10^{-9}$ amperes. The slopes of these curves give the $L$ values, the photomultiplier current per unit ion beam current.

2. The Luminescence Response to Various Ions as a Function of Energy

Plots were made of $L$ versus $E$ for each of the ions. These are shown in Figure 6.

There were gradual variations in sensitivity of the photomultiplier. Also, under ion bombardment, the phosphor may have been deteriorating slightly. It was found that, for a given ion, the $L$ values could vary by as much as 10% from one day to the next. This effect introduced a difficulty in comparing the $L$ values for different ions. To surmount this difficulty, the values were normalized to a standard in the following manner: After the plots had been obtained for each of the ions
Figure 5. Photomultiplier current versus ion beam current. Lithium ions at 50.5 keV bombarding Zn$_2$SiO$_4$·Mn.
Figure 6. Observed L values versus energy for various projectiles bombarding Zn$_2$SiO$_4$:Mn.
separately, the filament was coated with two or more substances to obtain different projectiles. For these, L values were again observed at 3 different accelerating potentials over a short period of time in which the sensitivity of the photomultiplier did not change appreciably. In this manner, the various L values could be compared.

3. The Spectral Distribution

A check was made on the energy dependence of the spectral distribution of the luminosity of the phosphor. Under bombardment by ions, the phosphor appears to be a bright green. Most of the luminescence is at about 5500 Å. A mercury yellow transmission filter 5780 Å (Leybold type 46830), was inserted between the phosphor and the photomultiplier. Through this filter, the glowing phosphor appeared to be a dim yellow. With the filter in place, the L versus E curve for lithium ions as projectiles was observed. The results of this experiment are shown by the squares in Figure 7. Also shown in this figure are the L values obtained without the filter. It can be seen that the filter reduces the L values by a factor of 90 but that, within experimental error, the energy dependence is the same. This strongly suggests that there is no change in the spectrum of the luminescence with changes in the energy of the projectiles. This agrees with a previous experiment conducted on the luminescence of ZnS:Ag by Eve and Duckworth (1958). Thus the photomultiplier current will always be proportional to the number of photons per second being emitted from the phosphor.
Figure 7. Observed L values versus energy for lithium ions bombarding $\text{Zn}_2\text{SiO}_4$:Mn. The L values indicated by squares have been multiplied by 10.
4. The Effect of Filled Electron Traps

The Zn$_2$SiO$_4$:Mn phosphor has what are known as electron traps associated with the impurity centres. These traps are responsible for thermoluminescence. To investigate if filled traps just below the conduction band cause any appreciable portion of the luminescence response to ion bombardment, the following experiment was done: The target was cooled to liquid air temperature. It was then irradiated for 10 minutes with ultraviolet light with a wavelength of 2700 Å. After the irradiation, it was bombarded with Na$^+$ ions and the light output was recorded. The phosphor was then heated gradually to about 100°C. As the temperature rose, the thermoluminescence peaks were observed. The response to sodium ion bombardment was observed periodically while the phosphor was being heated. No difference in the ionoluminescence response could be detected.

The significance of this test is that, within experimental error, the response to ion bombardment is independent of the degree to which the traps are occupied by electrons. Hence, the response is due mainly to interaction between the projectiles and the electrons in the valence band rather than the electrons in the traps.

5. The Luminescence Response to Proton Bombardment

The curve for the hydrogen ions shown in Figure 1 was obtained by using a gas ion source so that a proton beam of 10$^{-11}$ amperes was obtained. L values were then obtained for energies from 5 to 15 keV. Van Wijngaarden's results were then normalized to these ones, providing an L versus E curve for energies up to 70 keV which could be compared directly to the curves for the other ions.
CHAPTER IV

1. Interpretation of Results

The plots shown in Figures 3 and 6 provide a comparison between experiment and theory, with the assumption that $C$ is the same constant for all projectiles. As was already demonstrated by the linear plot shown in Figure 1, the energy dependence of the light output for the hydrogen ions agrees, within experimental error, with theory. However, the experimental results show a much greater difference in light output between lithium and hydrogen than is predicted by the theory and the assumption of $C$ being the same for both projectiles. Furthermore, the experimental curves for lithium, sodium, potassium, rubidium, and cesium ions are all about 10% steeper than the theoretical curves.

It is not surprising that $C$ decreases as the mass of the projectiles increases.

Classically, if a heavy particle collides with a much lighter one, the maximum velocity which can be imparted to the lighter particle is twice the relative velocity between the two particles before the collision. Thus, in a given range of projectile energies, a lighter projectile will, on the average, impart more energy to an electron with which it is in collision than will a heavier projectile. An electron in the valence band of the $2H_2SiO_4 : Mn$ phosphor must receive at least 2.2 eV from the projectile in order to attain an energy state from which it can make a transition which will result in the emission of a photon.
From the preceding discussion it is expected that, in the case of the heavier projectiles, fewer of the electrons will be excited by 2.2 eV than in the case with lighter ions. Thus electrons excited by less than 2.2 eV, in returning to the valence band, will undergo non-radiative transitions. Thus the light output will not be directly proportional to the total amount of energy transferred from the projectiles to the electrons, since the ratio of radiative to non-radiative transitions is expected to be dependent on the velocity of the projectiles. This effect should explain why the observed L versus E curves of Figure 6 are more widely spaced than the curves in Figure 3 and also why the curves of Figure 6 are steeper than in Figure 3 for all of the ions except hydrogen. In the case of the hydrogen ions, the good agreement with the theory may be attributable to the fact that this ion is light enough that, in the energy range investigated, it transfers at least 2.2 eV to an appreciably large fraction of the electrons it interacts with.

Table I shows the relative C values for various ions at 20 keV.

**TABLE I**

<table>
<thead>
<tr>
<th>PROJECTILE</th>
<th>C VALUE</th>
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<tr>
<td>1H</td>
<td>$C_H$</td>
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<tr>
<td>3Li</td>
<td>0.144$C_H$</td>
</tr>
<tr>
<td>11Na</td>
<td>0.077$C_H$</td>
</tr>
<tr>
<td>19K</td>
<td>0.074$C_H$</td>
</tr>
<tr>
<td>37Rb</td>
<td>0.094$C_H$</td>
</tr>
<tr>
<td>55Co</td>
<td>0.060$C_H$</td>
</tr>
</tbody>
</table>
Multiplying the theoretical L values by the appropriate C value from this table will cause the theoretical and the observed L values to coincide at 20 keV. It will be noted that the relative C values for 11Na, 19K, 37Rb, and 55Cs are roughly the same.

Our results for 3Li, 11Na, 19K, and 37Rb are in approximate agreement with those of Eve and Duckworth (1958). In their experiment, the projectiles were in the energy range 4 - 25 keV. However, their L versus E curves are about 25% steeper than ours. Their experiment was done at pressures as high as a few times $10^{-5}$ Torr. Thus there may have been a dirt layer on their phosphor sample. This would decrease the light output at lower energies by absorbing energy from the projectiles.

2. Conclusion

It appears that our experimental results can be fairly well interpreted with the theory developed in Chapter I. To our knowledge, no other fruitful attempts have been made to explain the energy dependence of ionoluminescence. Moreover, the so-called threshold energy for protons can now be understood on the basis of our theory. At the lower energies, the relative importance of the nuclear collisions increases as the energy decreases. For this reason, the tangent to the straight part of the curve shown in Figure 1 does not pass through the origin, but predicts the threshold energy.

To explain the relative light outputs for the various ions, and to obtain better agreement with the observed energy dependence of the L values, the theory will have to take into consideration the velocity dependence of C.

Further experimental work will be necessary.
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VITA AUToris

1953 - graduated from J.L. Forster Collegiate, Windsor.
1958 - Bachelor of Science in Radiophysics, University of Western Ontario.
1963 - entered the Faculty of Graduate Studies of University of Windsor to study toward the M.Sc. degree in Physics.