A CLOUD CHAMBER STUDY OF PAIR PRODUCTION

by

HARRY BERNARD WOLFE

A THESIS SUBMITTED IN PARTIAL FULFILMENT
OF THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF ARTS

in the Department
of

PHYSICS

We accept this thesis as conforming to the standard required from candidates for the degree of MASTER OF ARTS.

Members of the Department of Physics

THE UNIVERSITY OF BRITISH COLUMBIA

April, 1951
A CLOUD CHAMBER STUDY OF PAIR PRODUCTION

ABSTRACT

The present status of the Bethe-Heitler theory of pair production is analysed, and results are given which can be compared with experiment. The main points of interest in the pair formation process are the cross-section, energy and angular distribution of the electrons, the momentum imparted to the nucleus, and the manner in which these factors vary with photon energy and atomic number. Although the assumptions involved, such as the Born Approximation, appear to be justified, a review of the literature shows that experimental results have not always been in entire agreement with theory. For instance, the experimental distribution of $E_e - E_+ \text{ follows neither the Bethe-Heitler nor the Jaeger-Hulme theory.}$

The proposed experiment is to be carried out with a cloud chamber using Xenon as the gas, and ThC as the $\gamma$-ray source. The errors involved in the method are discussed. To minimize scattering error a new method of analysis of cloud chamber tracks is suggested, in which the angle between successive equidistant chords is measured.

The nine inch chamber is of the rubber diaphragm type. The operation of the chamber and camera has been made entirely
automatic. The magnetic field is obtained by a pair of Helmholz coils. Two General Electric F.T. 126 flash lamps provide sufficient light for photography. Stereoscopic pictures are obtained by the double mirror method. A great number of difficulties had to be overcome, especially in the functioning of the expansion valves, in order to get good electron tracks and consistent operation.

It has been found that it is very important to use correct procedure in filling the chamber and "cleaning" it out for the production of tracks. Very nice electron tracks have been obtained with a ThC\textsuperscript{2} source and Argon in the chamber. Preliminary observations indicate that the source may need to be shuttered, and that the chamber will need a thin window.
ACKNOWLEDGEMENTS

The author wishes to express his appreciation to Dr. J. B. Warren for suggesting the topic and for his continued interest in the work. Special thanks are also due to Mr. K. L. Erdman, for his assistance in the design and construction of some of the auxiliary apparatus.

Part of the work was done while the author was a holder of a National Research Council Bursary (1949-50).
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACKNOWLEDGEMENTS</td>
<td></td>
<td>Front</td>
</tr>
<tr>
<td>ABSTRACT</td>
<td></td>
<td>Front</td>
</tr>
<tr>
<td>I THEOR Y OF PAIR PRODUCTION</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. Dijac's &quot;Hole&quot; Theory</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>2. Cross-section</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>3. Angular Distribution</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>4. Nuclear Recoil</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>5. Corrections</td>
<td></td>
<td></td>
</tr>
<tr>
<td>a. Born Approximation</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>b. Screening</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>c. Interaction</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>6. Other Types of Pair Production</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>II COMPARISON OF THEORY AND EXPERIMENT</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. Experimental Method</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>2. Energy Distribution</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>3. Cross-section</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>4. Angular Distribution</td>
<td>11</td>
<td></td>
</tr>
<tr>
<td>5. Nuclear Recoil</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>6. Difference of Energy $E_+ - E_-$</td>
<td>13</td>
<td></td>
</tr>
<tr>
<td>7. Summary</td>
<td>14</td>
<td></td>
</tr>
<tr>
<td>III PROPOSED EXPERIMENT</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. Aim of Experiment</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>2. Discussion of Errors</td>
<td></td>
<td></td>
</tr>
<tr>
<td>a. Scattering</td>
<td>17</td>
<td></td>
</tr>
<tr>
<td>b. Projection of the Track</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>c. Energy Loss</td>
<td>21</td>
<td></td>
</tr>
<tr>
<td>d. Turbulence</td>
<td>21</td>
<td></td>
</tr>
<tr>
<td>3. Method of Analysis</td>
<td>22</td>
<td></td>
</tr>
<tr>
<td>IV APPARATUS AND EXPERIMENTAL WORK</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. Cloud Chamber</td>
<td>24</td>
<td></td>
</tr>
<tr>
<td>2. Valves</td>
<td>26</td>
<td></td>
</tr>
<tr>
<td>3. Control Circuit</td>
<td>27</td>
<td></td>
</tr>
<tr>
<td>4. Lights</td>
<td>28</td>
<td></td>
</tr>
<tr>
<td>5. Camera</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>6. Collimator</td>
<td>31</td>
<td></td>
</tr>
<tr>
<td>7. Reprojection</td>
<td>32</td>
<td></td>
</tr>
<tr>
<td>V RESULTS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. Operation of the Chamber</td>
<td></td>
<td></td>
</tr>
<tr>
<td>a. Filling the Chamber</td>
<td>34</td>
<td></td>
</tr>
</tbody>
</table>
b. Clearing Process 35

2. Observations with a \( \gamma \)-source
   a. Experimental Arrangement 39
   b. Pictures 40

APPENDIX -- Continuously Sensitive Cloud Chamber 43

BIBLIOGRAPHY 46

LIST OF REFERENCES 47
LIST OF FIGURES

1. Energy Distribution of Pairs  Following 2
2. Cross-section for Pair Production  Following 2
3. Distribution of Recoil Nucleus  4
4. Energy Distribution of Positrons  4
5. Angular Distribution of Positrons  12
6. Distribution of $E_1$-$E_2$  Following 13
7. Error from Projection of Cloud Chamber Track  21
8. Geometrical Analysis of Cloud Chamber Track  22
9. Circuit Diagram of Step-Switch  Following 27
10. Plan View of Camera  Following 30
11. Circuit for Automatic Camera Operation  Following 31

TABLES

1. Pair Cross-Section per Atom of Pb.  6
2. Distribution of Nuclear Recoil  13
3. Expected Number of Tracks in Xenon  16
LIST OF PLATES

Following Page

1. Filling Tube 25
2. Minor Expansion Valve 25
3. Main Expansion Valve 26
4. Control Circuit 27
5. Wiring Diagram for Lamps 28
6. Diagram of Chamber, Coils, and Mirror Stand 30
7. Source Collimator 31
8. Picture of Collimator Beam 31
9. Tilting Table for Reprojection 32
10. Schematic Diagram of Experimental Arrangement 38
11. Cloud Chamber Apparatus 39
12-15. Electron Tracks 40
16. Electron Tracks 42
17. Diffusion Cloud Chamber 43
I -- THEORY OF PAIR PRODUCTION

1. **Dirac's Hole Theory**

Dirac's relativistic wave equation for a free electron gives rise to solutions for which the energy is negative. This is because the energy for a free particle can be written,

\[ E = \sqrt{p^2 + m^2c^2} \]

These states of negative energy at first gave rise to serious difficulties in interpretation. Dirac's "hole" Theory gave the connection between these states and the observed positrons -- electrons with a positive charge. According to this theory an external field acting on the electrons in the negative energy states with energy \( E = -|E| \) and momentum \( \vec{p} \) can cause a transition to a state with positive energy \( E' \) and momentum \( \vec{p}' \). Thus we obtain a positive and negative electron pair with

\[
\begin{align*}
\vec{p}_e &= -\vec{p} \\
E_e &= -|E|
\end{align*}
\]

\[
\begin{align*}
\vec{p}_+ &= \vec{p}' \\
E_+ &= E' = -E
\end{align*}
\]

That is, the "hole" (positron) in the negative energy distribution has a positive charge and positive energy and a momentum opposite to that of the negative energy state. The energy required for this transition is \( E' - E = E_+ + E = 2mc^2 = 1.022 \text{ Mev} \).

This energy can be supplied through the absorption of a \( \gamma \)-ray or by impact with an energetic particle. Another particle, a nucleus for example, must be present to conserve energy and momentum.

2. **Cross-Section**

The possibility of pair production by a \( \gamma \)-ray in the field of
a nucleus was first pointed out by F. Perrin. The equations describing the behaviour of an electron interacting with a radiation field are far too complicated to be solved exactly. In all application of the theory, the interaction energy is considered as small and approximate solutions are obtained which are correct only to the first order in this energy. In 1933 Plesset and Oppenheimer gave a provisional order of magnitude for the cross-section of pair production as

\[ \phi = \frac{Z^2}{r_{137}} \left( \frac{e}{mc^2} \right)^2 = \varepsilon \cdot \mathbf{7} \times 10^{-28} \ v^2 \ s \ y. \]

where \( Z \) is the charge on the nucleus. The first comprehensive treatment of pair production was provided by Bethe and Heitler.

In this treatment, the perturbation \( H' \) causing the transition consists of two parts:

(1) \( H \), the interaction of the light quantum \( k \) with the electron, and

(2) \( V \), the interaction of the electron with the nucleus.

The process is considered as the reverse of Bremsstrahlung, except that the energy in the final state is negative. The result for the cross-section for creation of a positive electron with energy \( E_+ \) and a negative one with energy \( E_- \) is

\[ \Phi_{E_+} dE_+ = \frac{1}{4} \frac{e^2}{E_+^3} dE_+ \left\{ -\frac{4}{3} - 2E_+E_- \frac{p_+^2 + p_-^2}{p_+^2 p_-^2} + \frac{\mu^2}{p_+^2 p_-^2} \left( \frac{E_+}{p_+^3} + \frac{E_-}{p_-^3} - \frac{E_+ E_-}{p_+^2 p_-^2} \right) \right. \]

\[ + \left[ \frac{k^2}{p_+^2 p_-^2} \left( E_+ E_- + p_+^2 p_-^2 \right) - \frac{8}{3} \frac{E_+ E_-}{p_+^2 p_-^2} - \frac{\mu^2}{p_+^2 p_-^2} \left( E_+ E_- p_+^2 + E_+ E_- p_-^2 \right) \right] \]

\[ + \left. \left. \frac{2k E_+ E_-}{p_+^2 p_-^2} \right\} \right\} - \left( 1 \right) \]

where \( \epsilon_+ = 2 \log \frac{E_+ + p_+}{\mu} \), \( L = 2 \log \frac{E_+ + p_+ p_+ + \mu^2}{\mu \hbar} \), \( \Phi = \frac{Z^2}{r_{137}} \)

\( \hbar = \hbar \sqrt{ } \), \( \mu = mc^2 \), \( r_0 = \frac{e^2}{mc^2} = \text{classical electronic radius} \).
FIGURE I

DISTRIBUTION OF POSITRON ENERGY

\[ \frac{\phi_{E^+}}{\phi} \]

FIGURE II

CROSS-SECTION FOR PAIR PRODUCTION

\[ \frac{E^+ - mc^2}{\hbar^2 - 2mc^2} \]
The energy distribution is plotted in figure 1. The cross-section is given for the creation of a positive electron with kinetic energy $E_+ - mc^2$. The numbers affixed to the curves refer to the $\gamma$-ray energy in units of $mc^2$. The curves for $k = 6$ and $10 mc^2$ are valid for any element; the curves for the higher energies, for which screening is effective are calculated for P.b. For very low quantum energy the distribution has a broad maximum where both electrons receive the same amount of energy. For very high energies the distribution has two maxima where one of the electrons has a very small and the other one a very large energy. Finally, the distribution tends to an asymptote curve ($\infty$).

By integrating equation (1) over all possible $E_+$, one obtains the total cross-section for pair production. The result is plotted in figure 2 with the cross-section in units $\Phi = \frac{E_r}{137}$. The dotted curves show the cross-section for Compton scattering as comparison. We see from the graph that the behaviour for Compton scattering is entirely different to that for pair production. For small energies the probability of pair formation is generally much smaller than that for the Compton effect, while at high energies the pair formation is much more frequent than the scattering.

3. Angular Distribution

The number of electrons or positrons emitted at an angle $\theta$ to the $\gamma$-ray is approximately proportional to

$$\Phi(\theta)d\theta = \frac{\theta d\theta}{(\theta_+ \theta^i)^2}, \quad \theta \sim \frac{mc^2}{E}$$

Thus the average angle is of order $\theta \sim \frac{mc^2}{E}$. Bethe obtained
this expression by suitably integrating Equation (1), under the assumption that the potential due to the atomic nucleus fell away exponentially as the distance from the nucleus.

4. **Nuclear Recoil**

A certain momentum $\vec{q}$ will always be transferred to the nucleus, where

$$\vec{q} = \vec{k} - \vec{p}_s - \vec{p}_t \tag{2}$$

The nuclear impulse will have its smallest value when all the momenta are parallel; in this case $q_{\text{min}} = S = k - p_s - p_t$. Bethe has shown that most of the pair creations involve a momentum transfer between $S$ and $m_c$ to the nucleus, and that the probability $\Phi(q)$ is proportional to $q$ in this region. Recent calculations by Jost et alia employing Feynman's methods have given results whose general behaviour do not differ appreciably from those of Bethe. Figure 3 shows the typical momentum and angular distribution of the recoil nucleus for a $\gamma$-ray energy of 4.08 Mev.

**FIGURE 3**

![DISTRIBUTION OF RECOIL NUCLEUS](image)
5. Corrections

(a) Born Approximation

We note that equation (1) and the curves in figure 1 are symmetric in the energy distribution between the positive and negative electrons. This is a result of using the Born approximation, where $V$ occurs squared and the sign of the charge disappears. The limit of validity for this approximation is $\frac{1}{\hbar v} << \frac{1}{\ell}$, where $v$ is the velocity of either electron. If this is not satisfied then the exact wave functions must be used. In the exact calculation the positive electron $e^+$ would have more energy than the negative electron $e^-$, because of repulsion of the $e^+$ and attraction of the $e^-$ by the nucleus. Bethe and Heitler estimated the average difference in energy to be $2mc^2Z/137$.

Jaeger and Hulme have treated the problem rigorously, using spherical wave functions and only numerical approximations. The results of their calculations for lead are shown in Figure 4 and Table 1, where Bethe and Heitler's results are given for comparison. The experimental points of Alchanow, Alchanian and Kosodaew for Th C\textsuperscript{111} $\gamma$-rays (5.2mc\textsuperscript{2}) are included in the graph. The electrons will of course, have the same distribution with the kinetic energy scale replaced by (1600 KeV - positron energy). Jaeger and Hulme's method gives somewhat higher values than those of Bethe and Heitler, but it shows that the Born approximation should be good at high energies for even heavy elements.
Table 1

<table>
<thead>
<tr>
<th>h(\gamma/mc^2)</th>
<th>(\sigma \times 10^{24})</th>
<th>(\sigma \times 10^{2d}(B.H))</th>
<th>(E_+ - E_-)</th>
<th>(E_+ - E_-(B.H))</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>0.67</td>
<td>0.34</td>
<td>0.33 Mev</td>
<td>0.6 Mev</td>
</tr>
<tr>
<td>5.2</td>
<td>3.1</td>
<td>2.5</td>
<td>0.55</td>
<td>0.6</td>
</tr>
</tbody>
</table>

Figure 4

ENERGY DISTRIBUTION OF POSITRONS

(b) Screening

For equation (1) to be valid, the energies of both electrons must not be so large that the Coulomb screening by the orbital electrons becomes effective, i.e., \(2E_+ E_- / h \nu < 137Z^{-1/2} mc^2\). Thus screening becomes effective only at energies large compared with \(mc^2\). This is because the pair creation can take place at a greater distance from the nucleus, and thus the effective nuclear Coulomb field is lessened by the outer electrons. Wheeler and Lamb\(^8\) have pointed out however, that in the latter case energetic quanta will produce pairs at a greater rate because of the additional possibility of collisions in which the atom is excited.
(c) Electron Interaction

In the present theory there is no satisfactory way to include the interaction $V_{+\pm}$ between the positive and negative electron. Heitler$^9$ states that $V_{+\pm}$ is probably the matrix element of a Coulomb interaction belonging to a transition from a positive energy state $\vec{p}$ to a state with negative energy and momentum $-\vec{p}$, and will vanish when momentum is conserved. Thus $V_{+\pm}$ can be neglected in the approximation.

6. Other Types of Pair Production

Besides production by a photon in the field of a nucleus, pairs can also be created if a heavy particle with kinetic energy greater than $2mc^2$ collides with another heavy particle$^9$. Other possibilities of theoretical interest only are the production of pairs in vacuum by two quanta of combined energy greater than $2mc^2$, or by fast electrons passing through the field of a nucleus$^{10}$. Of greater experimental importance is "triplet" production - the formation of a pair by a photon in the field of an electron. This has received considerable interest$^{11-14}$ in the literature lately, but will not be discussed in detail here since the cross-section is small except at high energies. It has been shown that the threshold energy for this process is $4mc^2 = 2.04$ Mev. The cross-section should be proportional to $Z$, there being $Z$ electrons about a nucleus of charge $Z$. In contrast to pair production in the field of a nucleus, the recoil electron may receive considerable energy. In a cloud chamber we will therefore see a "triplet" -- one positive and two
negative electrons starting at a common apex.

II -- COMPARISON OF THEORY AND EXPERIMENT

1. Experimental Methods

We have seen that the main points of interest in pair production by a photon are the cross-section, the energy and angular distribution of the electrons, the impulse communicated to the nucleus, and the manner in which these factors vary with the incident photon energy and the atomic number of the interaction nucleus.

Accurate experiments on the phenomenon cannot be carried out with plates or foils, since the electrons are strongly scattered and absorbed. To avoid multiple scattering, the foil must be thinner than the thickness given by Wentzel's criterion: $t < \frac{2}{\pi^2 n}$, where $p$ is the effective radius of the atom and $n$ is the number of atoms per c.c. Thinner foils of course, mean fewer events. Consequently, accurate results of energy distribution might be obtained, but not of angular distribution.

It seems that the most reliable method of investigation so far is in the gas of a Wilson cloud chamber, but, under such conditions, statistics are very poor because of the small cross-section. Moreover, the work is very tedious and the measurements difficult. Energy measurements are somewhat dubious in this case because of multiple scattering in the gas distorting the curvature (but not as badly as with foils). Angular measurements are probably correct as we can see the effect of large deviations and small angle
scattering is not very serious. Thus, early investigations\textsuperscript{16-19} of pair production by cloud chambers are unreliable chiefly because of insufficient statistics. For instance, Simons and Zuber\textsuperscript{18} obtained a total of only forty-four pairs in Argon and Methyl Iodide. Their results were therefore subject to a great deal of statistical error, especially in the angular and energy distribution measurements.

Pair spectrometer experiments would probably be good to determine the dependence of cross-section on Z and quantum energy (except perhaps at low energies). Energy and angular distributions could not be obtained by this method, however.

Statistics would probably be considerably improved if one could devise a counter which would distinguish between positrons and electrons. This might be done by employing a scintillation counter to detect the annihilation positron radiation from a \( \beta^- \) counter. One could thus get the angular distribution from coincidence experiments. It might also be possible to put the electron counter in a confined magnetic field to make it proportional, and thus obtain the energy distribution in addition.

2. Energy Distribution

The first investigation involving sufficient statistics was carried out by Groshev\textsuperscript{20}, who obtained 435 pairs in nitrogen, krypton, xenon, using the 2.62 Mev \( \gamma \)-rays from ThC\textsuperscript{n}. His results were only qualitatively in agreement with the theoretical calculations of Jaeger and Hulme\textsuperscript{6}, showing a slight asymmetry towards the positrons in the energy distribution. A later investigation by
Roy with the γ-rays of Ra (2.2 Mev) also showed only qualitative agreement. However, this latter experiment was carried out with foils of various metals, introducing the errors mentioned above. A very recent experiment by Powell, Hartsough, and Hill on the bremsstrahlung of 322 Mev electrons (1060 pairs), gives agreement with the theoretical curves, showing two maxima as predicted.

3. Cross-section

The Wilson Cloud Chamber permits a direct determination of cross-section. One counts \( N_1 \), the number of pairs, and \( N_2 \), the number of Compton recoil electrons. Thus we get a ratio of the cross-sections:

\[
\frac{\phi_p}{\phi_c} = \frac{N_1}{N_2}
\]

\( \phi_c \), the cross section for the Compton effect, is well known from the Klein-Nishina formula, and thus the cross-section for pair production \( \phi_p \) can be calculated. Although this determination is simple in principle, in practice it is very difficult to obtain the exact number of Compton and pair tracks originating in the same volume of the chamber. For a γ-ray energy of 5.2 mc² and \( Z = 82 \) (Pb), the theoretical ratio is 0.20. An early experimental value of 0.22 is shown in Figure 2.

Benedetti verified the proportionality of cross-section on \( Z^2 \), employing counter techniques. Groshev also checked the dependence on \( Z^2 \) using the above method, but theoretical values were twice as great as the experimental values obtained.

Most experiments on cross-section for pair production have been indirect. By measuring the total absorption coefficient of
\( \gamma \)-rays, that is the sum of the Compton, photoelectric, and pair processes, one obtains an indirect value of the pair cross-section from a knowledge of the other two cross-sections. Davisson and Evans found very good agreement with theory for \( \gamma \)-rays from 0.8 to 2.8 Mev, using various metals. A good summary of the work to date is given in their report. A magnetic pair spectrometer experiment by Walker employing 17.6 Mev \( \gamma \)-rays also gives good agreement with the Bethe and Heitler values corrected for screening, except at high Z (Pb). Lawson and Adams also found the absorption coefficient for Pb to be about 10% too low at 88 and 19 Mev respectively.

4. Angular Distribution

According to the Bethe and Heitler theory the average angles \( \bar{\theta}_- \) and \( \bar{\theta}_+ \) of the positron and electron with the incident photon, should both be of order \( \frac{mc^2}{E} \). This is about 11° for 2.62 Mev. Groshev found however, that the average angle was much larger than this (about 25°), and also that \( \bar{\theta}_- \) was larger than \( \bar{\theta}_+ \). The experimental curve of Roy follows the general shape of the theoretical distribution, but the maximum is shifted towards larger values. (See Figure 5). Roy found an average angle of 30° between electron and positron, and a 3° difference in \( \bar{\theta}_- - \bar{\theta}_+ \). A recent experiment by Koch and Carter (thirteen hundred pairs) with betatron white radiation also found \( \bar{\theta} (\text{max}) \) for both positrons and electrons for various energies all higher than corresponding theoretical values. \( \bar{\theta}_- \) was larger than \( \bar{\theta}_+ \) except in the lowest energy range.
5. Nuclear Recoil

The nuclear momentum $q$ has been calculated for 76 pairs in N and 29 pairs in Kr by Groshev and Frank (See reference 20). This is done by measuring the experimental momentum of the pair (the vector sum of positron and electron momenta) and solving for $q$ in equation (2). Thus the reliability is dependent on the accuracy with which one can measure both positron and electron energies and the angle between them. Modesitt and Koch\textsuperscript{27} have also investigated recently the nuclear recoil of the pairs from the betatron white radiation\textsuperscript{26}. No other experimental work on nuclear impulse during pair formation has been reported in the literature. The results of Modesitt and Koch agree in every field of comparison with the work of Groshev and Frank, for comparable energy ranges (2.62 Mev). Their results are compared in Table 2.
The experimental results indicate a most probable value of momentum transfer near $mc$ and a rapid decrease in probability in both directions away from $mc$. If we compare their values with those in Figure 3, the experimental curves are found to be too low for smaller angles and too high for high momentum transfers, the disagreement for the momentum distribution being particularly sharp. They did not find a decrease of average momentum with increasing quantum energy as predicted by theory. The average momentum $\bar{q} = 1.6$ mc for the experimental range 8-11 Mev is in disagreement with the value 1.0 mc calculated by Rosenbaum for a quantum energy of 10.2 Mev.

6. Difference of energy $E_r - E_\gamma$

In Figure 6 I have plotted the theoretical curves of Bethe and Heitler and of Jaeger and Hulme for $E_r - E_\gamma$ against $Z$. The points found by various experimenters are also plotted. As we see there does certainly appear to be a dependence on $Z$. The "exact" curve of Jaeger and Hulme also appears to a better approximation than that of Bethe and Heitler, but this is by no means conclusive.
Figure 6

DISTRIBUTION OF $E_+ - E_-$

- Key
  - Groshev
  - Simon and Zubber
  - Niwa and Kozima

Beckett and Hether Theoretical Curve

Jagger and Holme Theoretical Curve
7. **Summary**

Figure 6 seems to exemplify the present state of affairs in the description of the pair creation process. We have seen that there is only qualitative agreement between theory and experiment in all phases of pair production. Moreover, the experimental results of various authors are not too consistent within themselves for many aspects. There appears to be a great need for further work to be done in checking and extending these results.

Lawson\(^ {29} \) has discussed the limitations of the Bethe and Heitler theory, and believes that this theory is not suitable for precise comparison with experimental results. For \( \gamma \)-rays of less than 3 Mev Lawson states that Jaeger and Hulme's calculation gives a correction of opposite sign to that required. The disagreement between theory and experiment arises since the Born approximation may not be applicable for heavy elements, while for light elements the Fermi-Thomas statistical gas model of the atom is not trusted.
III → PROPOSED EXPERIMENT

1. Aim of Experiment

Previous investigations have suffered chiefly from insufficient statistics. In the present cloud chamber experiment, it is hoped to increase the number of events, by using a stronger source of gamma radiation than available to earlier workers, and a high Z gas. It would be of great interest to use a gaseous lead compound, but there are none with sufficient vapour pressure. The most suitable gas appears to be Xenon (Z = 54). Xenon has the additional advantage of being monatomic, so that a low expansion ratio can be used to attain sufficient supersaturation for the formation of tracks. The experiment is first to be carried out with the 2.615 Mev γ-rays\(^\text{32}\) from a 30 millicurie source of ThC\(^\text{22}\). Later it is hoped to extend the work in conjunction with the U.B.C. Van de Graaff generator, employing the 6.1 Mev γ-radiation from F (p, γ) and the 17.6 Mev γ's from Li (p, γ).

As we have seen in Section II, the experimental measurements of interest are the number of pairs and Compton electrons originating in the same part of the chamber (through which the collimated γ-ray beam passes), the angles which the pair members make with the γ-ray, and the energies of the positive and negative electron. The energies are obtained by measuring the radius of curvature \(\rho\) of the electron, in a known magnetic
field \( H \). The energy can then be read off directly from suitable graphs, where the kinetic energy of the electron is plotted against \( H \). Besides these measurements, we expect to have sufficient total track length to examine the pictures for single scattering, and annihilation of positrons in motion, as has been described by Ho Zah-Wei. Some incidental information should also be obtained on the relatively new field of investigation of "triplet" production.

### Table 3

<table>
<thead>
<tr>
<th>Source of radiation</th>
<th>( \text{ThC}^{\text{n}} )</th>
<th>( F(p, \gamma) )</th>
<th>( Li(p, \gamma) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy of quanta</td>
<td>2.62 Mev</td>
<td>6.1 Mev</td>
<td>17.6 Mev</td>
</tr>
<tr>
<td>Total number of quanta /sec.</td>
<td>( 10^9 )</td>
<td>( 3 \times 10^7 )</td>
<td>( 10^6 )</td>
</tr>
<tr>
<td>( \phi_{/\text{c.c.}} ) for pairs (sq.cm.)</td>
<td>( 2.86 \times 10^{-5} )</td>
<td>( 10.3 \times 10^{-5} )</td>
<td>( 22 \times 10^{-5} )</td>
</tr>
<tr>
<td>( \sigma_p/\sigma_c )</td>
<td>( 1/6.5 )</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>Number of pairs per picture</td>
<td>1</td>
<td>0.15</td>
<td>0.01</td>
</tr>
<tr>
<td>Number of Comptons per picture</td>
<td>7</td>
<td>0.15</td>
<td></td>
</tr>
</tbody>
</table>

In Table 3 I have calculated the approximate number of pairs and Compton electrons per picture, that we should expect with the various sources. These figures have been obtained assuming experimental conditions of 50 cm. pressure of Xenon in the chamber, a working volume of 20 c.c., and a sensitive time of 0.025 seconds. The callimator subtends 0.001 steradians.
at the source. (See Section IV). The results of the table should be interpreted only as relative orders of magnitude, because of the many assumptions involved.

The figures for the \((p, \gamma)\) radiation have been calculated assuming a 10 microampere beam of protons in the Van de Graaff generator, with a bombarding energy of 1 Mev. The yield measurements (disintegration per proton) are those of Fowler and Lauritsen for thick targets. If we assume that 25% of the pairs formed in the chamber will be suitably oriented for photography and measurement, we can see from Table 3 that it will probably require about 4000 pictures to get approximately 1000 good measurable pairs for the ThC\(^{235}\) source. About 25,000 pictures will be required to achieve the same statistics with the \(F(p, \gamma)\) radiation, with the same solid angle of .001 steradians subtended at the source.

2. Discussion of Errors
   (a) Scattering

   Bethe has pointed out that because of scattering, the evaluation of the curvature of a charged particle is significant only if the velocity \(v/\) is greater than a certain critical value. To reduce multiple scattering, a gas of low atomic number should be used, and high magnetic fields are also desirable. This is because the mean angle of deflection due to multiple
scattering in a given thickness of material, is inversely proportional to the kinetic energy of the particle \(^{37}\). The deflection due to a magnetic field is only inversely proportional to the momentum. Therefore, at sufficiently low velocities, the scattering effect will be greater than the curvature in the magnetic field. This is especially true for a gas of high atomic number (argon). In our experiment then, the member of the pairs with the greater kinetic energy, will have the lesser scattering error associated with it.

Bethe\(^{37}\) derives an expression for the apparent radius of curvature due to scattering as

\[ \rho_s = 4.04 \frac{E}{x} \left( \frac{x}{B} \right)^{1/2} \text{ cm}, \]

where \(E\) is the kinetic energy in Mev,

\(x\) is the distance through which the electron passes,

\(B\) is a correction factor close to unity,

and there are \(LP\) nuclei per c.c., where \(L\) is Loschmidt's number \((L = 2.7 \times 10^{19})\), and \(P\) is the number of atoms per molecule. The radius of curvature in a magnetic field is

\[ \rho_m = 1700 \frac{\beta}{H} \text{ cm}, \text{ where } \beta = \frac{v}{c}. \]

Comparing the two radii,

\[ \frac{\rho_m}{\rho_s} = \frac{\rho_0}{\rho_s} \]

with \(\rho_0 = \frac{L}{H} \left( \frac{B}{x} \right)^{1/2} \).

Below the "critical velocity \(\rho_0\)\), the major contribution to the curvature arises from scattering, and curvature measure-
ments are useless. For Xenon at 50 cm. pressure, x = 10 cm., H = 600 gauss, this critical energy is about 4 kev, and is thus not too significant in our experiment.

If we assume a verified multiple scattering law, Simons and Zuber\(^1\) have pointed out, that fluctuations of curvature as well as mean curvature can be utilized for energy (and mass) measurements. This can be done by dividing a strongly curved track into a number of sections, say of 1-cm. length, whose curvatures are measured separately. This procedure is specially adapted for tracks with sharp bends due to single scattering, since large differences can be eliminated.

Multiple scattering theories have been developed by Bothe\(^{38}\), Williams\(^39\), Molière\(^{41}\), and Snyder and Scott\(^{42}\). These have been summarized by Groetzinger et alia\(^{43}\) and compared with the scattering of 132 beta-particles. The angular deflection \(\phi\) of the tangent due to multiple scattering, as projected on a plane of incidence, is approximately normally distributed:

\[
\phi(\phi) = (2\pi\sigma^2)^{-1/2} \exp\left(-\frac{\phi^2}{2\sigma^2}\right) \phi(\phi)
\]

where the correction factor \(\phi(\phi)\) for plural and single scattering is important for large angles only. The variance, or mean square deflection \(\sigma^2\), can be expressed as a product of two factors Q and G, where Q depends on the interaction between the particle and the nuclei of the scattering atoms, while G
takes into account the structure of these atoms (screening, etc.), as well as statistical considerations. All the various theories give $Q$ as:

$$Q = 4 \pi N x e^4 \frac{Z^2}{p^2 v^2},$$

where $N$ is the number of nuclei per c.c., $x$ the thickness of the scattering substance, and $p$ and $v$ are the momentum and velocity of the particle. The theories differ in their expressions for $G$, as well as for $\phi$. Bothe effectively replaces $G$, which is approximately independent of mass and energy of the scattered particle, by the numerical value

$$G = 4.125$$

(b) Projection of the track

In analysing the curvature of the tracks, it is actually not too necessary to project on the plane of incidence of the track. Figure 7 gives the percentage error in the projected angle, if we project on a plane perpendicular to the direction of the magnetic field. $\alpha$ and $\alpha'$ are respectively the angles between the directions of the track at the beginning and end of the section, and the plane of projection. Under our experimental conditions this error is probably at most 0.5%. For large angles, one can of course project onto the plane of incidence.
(c) **Energy Loss**

Molière has shown that the effect of energy loss due to collision is negligible. For instance, for electrons with a final energy of 50 keV and a path length of 14 cm, in one atmosphere of argon, the difference is less than 1%.

(d) **Turbulence**

The error due to turbulence in the chamber is probably very small, since a low expansion ratio (1.1) is used with monatomic gases, such as argon and xenon. A few high energy cosmic ray tracks (probably protons) which occur incidentally in our pictures, are only slightly curved, indicating little if any turbulence.
3. Method of Analysis

Rather than measure the angles $\phi_i$ between the tangents to the projected track at certain division points, I propose instead to measure the angles $\omega$ between successive chords. (See Figure 8 where the curvature is exaggerated). This can be done by projecting the image of the track on a sheet of drawing paper giving the original size of the track, and then laying off, say 1 cm. sections by dividers. The sheet can be mounted on a drafting table, the points connected by straight lines, and the angles between successive chords measured by means of drafting machine. Let the mean of the angles be $\bar{\omega}$. Then if the section length is $x$, it follows from Figure 8:

$$
\rho^2 = x^2 \cos^2 \frac{\omega}{2} + (\rho - x \sin \frac{\omega}{2})^2
$$

$$
= x^2 + \rho^2 - 2x\rho \sin \frac{\omega}{2}
$$

$$
\therefore \rho = \frac{x}{2 \sin \frac{\omega}{2}} = \frac{x}{\bar{\omega}}
$$
if the angles involved are not too large (<15°). This method of analysis has the above mentioned advantage of minimizing scattering error, and thereby minimizes the standard deviation of \( \bar{\omega} \). It should be of interest to calculate the experimental standard deviation of the \( \omega_k \), and compare it with that of the various theories. Using the above method of analysis, I should estimate the random experimental error due to optics, photography, and personal error in measurement, to be less than 1°.
IV — APPARATUS AND EXPERIMENTAL WORK

1. Cloud Chamber

The cloud chamber used for this project is based on drawings obtained from the Chalk River Laboratories of the National Research Council (refer Chalk River Report P. D. 204 by E. Almqvist), and has been previously described by K. Parry. The whole cloud chamber unit has been assembled on a movable table for future use with the Van de Graaff generator of this department.

The chamber is the rubber diaphragm type, the expansion being effected by suddenly opening the back of the diaphragm to a very low pressure. It is ordinarily operated with the chamber gas at about two-thirds atmospheric pressure. The chamber itself consists of a plexiglass cylinder with dimensions 23 cm. inside diameter and 5 cm height. Two black aquadag rings are painted around the cylinder leaving a two cm. clear space in the middle to assist in collimating the lights. The background is formed by black velvet stretched over a round ring which makes a snug fit with the cylinder. The velvet makes a fair background for photography and helps eliminate turbulence set up in the chamber by the expansion. The plate glass roof has an aquadag ring painted around the outside, for the clearing field (1000 volts). A rubber tube, through which cold water continuously circulates,
is wound around the base. This is necessary to keep vapour from condensing on the glass roof, and also to keep the chamber temperature constant.

When the project was taken over, nice alpha tracks from Polonium and Radium sources were obtained and photographed. Electron tracks, having a much lower specific ionization, are more difficult to photograph and could not be obtained at this point. It was thought this was due to several causes: the chamber was not absolutely leak-tight, the rubber diaphragm seemed to be too sluggish in response, and the vacuum volume was too small for quick expansions.

In order to get the chamber leak-tight, a more uniform plexiglass cylinder was obtained and installed. Several types of rubber gaskets were tried, and very thin (1/32\textquotedbl) neoprene gaskets lightly coated with Silicone Dow-Corning grease were found to be the best. The grease softens the rubber and a better seal is obtained.

A new filling tube with a single outlet was installed. The base of the tube is soldered directly to the base plate of the chamber, since it was found after trying other methods that this was the only way to get that joint vacuum tight. A new cut-off valve of the bellows type was originally used. Although this system was very useful for operation, it proved eventually to be unsatisfactory — one could not be sure that
PLATE 1

GLASS GO TO STOP-COCK
RUBBER WASHER

BASE

FILLING TUBE FOR CHAMBER

PLATE 2

BAFFLE PLATE

MINOR EXPANSION VALVE

PIN TO SILENOID
the delicate bellows valve was always tight. Consequently, a glass stop-cock was attached to the filling tube, using a modified Wilson seal. This has proved to be very satisfactory and is absolutely vacuum tight. The filling tube and stop-cock are shown in Plate 1.

To obtain faster adiabatic expansions, a new diaphragm of first 1/8" natural rubber and later 1/16", was tried. The latter has proved satisfactory for our purposes. The expansion volume of three litres was increased to nine litres, by connecting three old mercury bottles in parallel. The system is mounted on a permanent frame underneath the chamber. A Welch vacuum pump with an operating capacity of 100 litres per minute continuously evacuates the bottles. The above adjustments considerably improved the speed of expansion.

2. Valves

A great deal of time has been spent on trying to stabilize the two valves which control the expansion of the cloud chamber. In my opinion they have not proved to be too satisfactory. The main expansion valve is the most important working mechanism on the chamber: it opens the back of the diaphragm to the vacuum, and closes off the vacuum tank for the compression (see plate 3). This valve has had to be refitted several times, and several solenoid pins tried. The original brass pin has been replaced by a steel pin 3/16"
in diameter, throughout its length, to avoid breaking by the sudden expansions and compressions. The valve relies on a grease seal to keep air from entering the expansion volume. This proved to be an unreliable vacuum seal. Any leaks will tend to slow down the expansions, and poor tracks will result. During the compression, the bellows must rest squarely on the rubber gasket to close off the vacuum. Adjustment of this can be made by rotating the solenoid pin at the bottom.

The secondary valve controls the slow expansions, which remove the old drops formed during the main expansion. The original butterfly-type valve was refitted several times, but the slow expansions were still unsatisfactory. A new "overhead" type valve was designed and built (Plate 2.). It was necessary to suspend a baffle plate above the valve, to prevent the rush of air forcing it shut. A spring was attached to the cannon solenoid pin, to prevent the lever from striking the valve too hard. The slow expansions are now quite satisfactory.

3. Control Circuit

The control circuit is essentially the same as that developed at Chalk River by the N.R.C. It consists of a series of timing circuits, using thyratrons and a grid condenser type of control. The condenser is charged up through
Figure 9

CIRCUIT DIAGRAM OF STEP SWITCH
a variable resistance, and the thyratron "fires" when the condenser voltage reaches the cathode potential of 200 volts. A pair of thyratrons, working as a long period multivibrator, actuates a 25 positron, 6 bank telephone-type selector switch. This switch controls the whole automatic operation of the chamber. (See Figure 9).

The circuit was constructed at a time when good components were unavailable. Consequently, the electronics continually broke down after a few hours of operation. Many parts of the circuit have had to be rewired in order to obtain stable operation. In addition, several modifications have had to be introduced. The selector switch has been rewired to actuate the minor expansion valve and the camera mechanism. To aid in the removal of old drops and ions, the clearing field voltage is on during the minor expansions as well, instead of only previous to the major expansion. The control circuit wiring diagram, including modifications, is shown in Plate 4.

4. Lights

The light sources are two argon-filled General Electric F. T. 126 repeat flash lamps, each with a peak output of twelve million lumens for an input of seventy-two joules per flash. In order to improve the characteristics of the light flash, a three millihenry inductance was added to the conven-
CIRCUIT FOR FLASH LAMPS
tional circuit. This allowed the lamps to dissipate 35% more energy, since it is the dissipation rate which sets the upper limit. The effect of the choke, as observed by a photocell connected to an oscilloscope, was to lengthen the light pulse from 350 microseconds to 1100 microseconds and to halve its height. This makes a better light pulse for photographic purposes, because the film reacts better to the slower pulse. The lights are discharged from a 96 microfarad condenser bank at 2000 volts. Since the lamps are 5½" long, they dissipate 17 joules / inch / flash.

Although the lamps are run over their recommended rating, no apparent ill effects have been observed. The triggering voltage from the Ford coil (10,000 volts) had to be carefully insulated from both chassis and lamp case. The wiring diagram for the lights is shown in Plate 5. For protection, the 2000 volt line and return is kept floating above ground by a 100K resistor, and in addition the condenser bank is discharged through a diode when the set is switched off.

It is very important to have as little light as possible reflected off the velvet and the top glass plate with a chamber as small as ours, this is difficult to achieve. In order to line the lamps up, a 5000 volt transformer fed off a variac is used to obtain a feeble light from the lamps, since the actual light flash is much too short to be easily registered on the eye.
5. Camera

The camera used in the investigation is a Kine-Exacta using 35 m.m. perforated film. It is equipped with a Zeiss-Tessar 3.5 lens, focal length 5 cm. Unfortunately, this focal length is not too suitable for taking stereoscopic pictures, since the camera must be mounted rather far from the chamber (28") with a consequent loss of light intensity. For instance, with a lens of focal length 4 cm., the camera could be mounted 22½" from the chamber, to achieve the same magnification, but the gain in light intensity would be over 50%. Another disadvantage is that only thirty-six pictures can be taken at one loading of the camera. For these reasons, it may be advisable in the future to obtain a different lens, and construct a camera especially designed for the purpose, and capable of taking, say a hundred feet of film at one loading.

The operation of the camera has been made entirely automatic and is controlled by the major control circuit. A solenoid, composed of 1500 turns of #28 copper wire wound on a brass form, develops enough force through a lever system to trip the shutter. This solenoid is designed to use 110 volts A. C., and holds the shutter open for approximately one-fifth second. The exposure time is therefore effectively the whole light pulse from the flash lamps. A small fractional
PLAN VIEW OF CAMERA
PLATE 6

DIAGRAM OF CHAMBER, COILS, AND MIRROR STAND
--horsepower motor winds the film and cocks the shutter through a system of gears. The motor trips a reversal switch to rewind itself. The 12 volts D.C. required for its operation is provided by a pair of storage batteries. The camera, solenoid, motor and reversing switch are mounted on a brass plate (Figure 10). This brass plate is fastened onto a reinforced stand which is rigidly attached to the Helmholz coils. The circuit for the automatic camera operation is shown in Figure 11.

Stereoscopic pictures are obtained by the double mirror method. Front-surfaced aluminum mirrors (14'' x 6½'') were made in the nuclear physics laboratory, according to the procedure described by Strong. Aluminum foil was vapourized on tungsten filaments in a large evacuated vacuum bottle, which was large enough to contain the clean plate glass. The aluminum adhered to the glass, making a good reflecting mirror surface. These mirrors are attached to the camera stand, just above the chamber top. The camera is mounted 28'' from the chamber. The distances are such that a double stereoscopic view of the centre portion of the chamber (through which the gamma ray beam passes) is obtained. The camera, stand, mirrors, and Helmholz coils are shown schematically in Plate 6.

6. Collimator

The collimator (Plate 7) for the source is designed
Figure 11

CIRCUIT FOR AUTOMATIC CAMERA OPERATION
Plate 7

SOURCE COLLIMATOR

Plate 8

Collimated Beam
to cut down scattered electrons and gamma rays. The seven sections required were cast from lead in brass forms. The ends of the sections were then machined, and the sections inserted into a snug-fitting brass cylinder. The total length of the collimator is 12", and there is 1" clearance between the end and the chamber wall. By removing the front section, brass or lead plugs can be inserted into the collimator to filter the beam.

A picture of the beam from the ThC" source as it enters the chamber is shown in Plate 8. This was obtained by prolonged exposure of a photographic plate wrapped in black paper. The impression on the plate indicates that the beam is well collimated, and is 1.1 cm. wide as it enters the chamber. A plate similarly exposed at the other end of the chamber indicates the beam is 2 cm. wide where it leaves the chamber. This corresponds to a solid angle subtended at the source of .001 steradians, and checks with the angle expected from the dimensions of the collimator.

7. Reprojection

In order to carry out measurements on the cloud chamber tracks, it is necessary to reproject them to their original size and position. To do this, the stand with the camera and mirrors attached is removed from the Helmholz coils and placed on the reprojection table. The film is then replaced
PLATE 9

SCREEN

SPRING

BALL AND SOCKET

VERTICAL ADJUSTMENT

BASE ADJUSTMENT

SET SCREW

TRIPOD BASE

TILTING TABLE FOR REPROJECTION
in the camera in the original position, the shutter is kept open and a strong light beam is aimed onto the film from above. The direct and stereoscopic images of the track are focussed onto the tilting table. The tilting table is then adjusted so that the images come together. The analysis of the tracks can then be carried out. (Sec. III - 3).

The tilting table was designed for speed and ease of adjustment. A cross-section view is shown in Plate 9. Rather than employ the usual slower hemispherical steel ball and magnetic clamping method, a brass ball and socket is used which can be rotated in any direction up to 30°. The ball is automatically held securely in any position by a spring. The tightness of the spring can be adjusted by a knurled knob. The screen consists of a 11" square aluminum plate, finished in white enamel so the image can be easily observed. This plate is fastened to a short rod which passes through the ball and socket. The assembly is mounted on a vertical shaft provided with a 2" drive, in order that it can be quickly adjusted to the correct height by rotating a knob. This shaft is held fast by tightening a set screw. The stable tripod base of the table is brought into correct horizontal alignment by a positioning screw. The vertical coordinate and the angle of dip that the table makes with the horizontal can be read directly from a steel rule and a compass.
1. **Operation of the Chamber**

   a. **Filling the Chamber**

   The following procedure has been developed for the filling of the chamber. The chamber is first put together, with the top glass plate as clean as possible. The vacuum pump is then attached to the filling tube through a T-joint. The chamber is pumped out for some time, say over-night, in order to remove all gases and condensed vapours. The filling tube stop-cock is then sealed off and the vacuum conditions are checked for a day or so, by means of a mercury manometer attached to the T-joint. The chamber must be absolutely leak-tight for proper operation, since leaks or eddies will distort the tracks or even prevent their formation.

   The gas (air, argon, xenon, etc.) is then admitted to bring the pressure up to the desired value, read on the manometer. This is usually about 50-60 cm. of mercury. The chamber is then sealed off by the stop-cock. The required liquid (about 5 c.c.), usually an alcohol-water mixture, is then admitted into the top of the filling tube. The liquid is allowed to pass slowly through the stop-cock. Some of the mixture should be kept in the upper tube, to prevent air entering the chamber. The volume admitted should be just in
excess of the amount necessary to saturate the gas in the chamber, since too much liquid will render the velvet a poor background for photography. The liquid remains suspended in the lower tube, and is allowed to evaporate and saturate the gas. The liquid must be renewed in the same manner, generally after ten days of operation, because the alcohol vapour diffuses through the rubber diaphragm. This latter effect is quite noticeable, since the odour of alcohol is very evident when the pump is first switched on, after the chamber has been idle for some time.

b. Cleaning Process

After the gas and vapour are introduced, no expansions are made until the movable plate controlling the expansion ratio is screwed up as far as possible, giving a very low expansion ratio. The chamber is then set in operation and expansions are made until any cloud formed shows signs of clearing up. This usually takes several hours, since the vapour must reach equilibrium and the dirt nuclei must be removed. The actual time required depends on the purity of the gas used. Tank gas is generally much cleaner than air, and can be cleared out sooner. The expanded time is set at about 30 seconds during this period, so that cloud drops formed on dust particles will have time to settle before the chamber is recompressed. The chamber expansions are observed by two
projection lamps aimed perpendicularly to the axis of vision, since the flash tubes give a far too brilliant and sudden illumination for easy visual observation.

As soon as the chamber is fairly clear, the expansion screw is rotated about 1/8 turn, and the process is repeated. As the correct expansion ratio is approached, tracks will appear fuzzy and diffuse at first, and the final good expansion ratio (for electron tracks) will be just below the cloud-formation limit. It has been found that this procedure cannot be hurried, since otherwise an over-expansion can occur and the chamber will be filled with a fog of tiny droplets. Several hundred small expansions may be necessary to remove this fog, even after only one over-expansion. Also, droplets condensing on the chamber roof may form a film on it. During the above cleaning process, the external room temperature (about 21°C) is kept constant by a mercury thermostat which controls several strip heaters. In addition, cold water is circulated through the coils and the pipe surrounding the base, at all times.

Once the chamber has been "cleaned" out, pictures can be taken continuously. One may have to adjust the expansion ratio slightly before commencing a set of pictures, to correct for any small changes in temperature. The above procedure must be repeated however, whenever additional liquid is
admitted to replace the vapour which has diffused through the rubber.

c. Expansion Cycle

The following cycle has been found suitable for rapid picture-taking, after the chamber has been cleared out.

(i) 0.0 sec. The chamber is compressed, ready for a main expansion, when the green light on the control panel goes on. The current through the Helmholz coils is adjusted manually to the correct value by the rheostat, and the lights in the room are put out. The solenoid for the overhead valve should be actuated during this compression.

(ii) 3.5 sec. The expansion takes place and the clearing field voltage is removed at the same time. The camera shutter is tripped by its solenoid.

(iii) 3.65 sec. The lights flash. It is important to adjust the light delay so that the drops have time to grow to full size, just before they start to fall. (Position 20 on the switch). Otherwise the tracks are very thin and photography is extremely difficult.

(iv) 28 sec. The chamber resets itself (compression). The clearing field goes back on. The camera motor winds the film and cocks the camera shutter for another picture.

Three clearing, or "minor" expansions follow, which remove the old drops. The compressed and expanded times are
the same for these as for the major expansion — that is, each expansion takes 28 seconds. The complete cycle requires 112 seconds.

It is a very interesting fact that the correct expansion ratio is a function of the compressed time. This effect is not too clearly understood, but it probably has to do with the attainment of both temperature and vapour equilibrium in the chamber. In any case, there is no point in having a longer expansion cycle with a small chamber, if the chamber is cleaned out and is functioning properly.

d. Photography

Kodak Ortho-Linagraph 35 m.m. film (clear base) has been found to be best for taking electron pictures. This is a fast orthochromatic film with a relative speed of 500 in the blue. It is therefore several times as fast as Super XX and is especially suitable for the light produced by the flash lamps. It is also a convenient film to work with, since a Wratten series 2 safety light can be used in the dark room with it. The clear base makes it very suitable for reproduction purposes. The film is less expensive if obtained in 100 foot reels. Strips of suitable length, say for thirty or thirty-five pictures, are cut off, trimmed, and wound in ordinary 35 m.m. cassetes. (See the Exacta Guide.) This operation takes perhaps a minute in the darkroom. After
SCHEMATIC DIAGRAM OF EXPERIMENTAL ARRANGEMENT
exposure the film is developed in Kodak D19 solution for fifteen minutes. This process of over-development increases the contrast between tracks and background. A stop-bath (Kodak SB-5) is used between developing and fixing. The whole development procedure can be carried out very efficiently in a Kodak Day-Light tank for 35 mm. film.

Pictures of electron tracks have been successfully taken at f 3.5 and f 4 with the Exacta camera. The latter stop is the better, because of the increased depth of focus.

2. Some Observations With a γ-ray Source

a. Experimental Arrangement

A schematic diagram of the experimental arrangement is shown in Plate 10. The filtered and collimated γ-ray beam from the ThC" source enters the chamber perpendicularly to the axis of the camera, and parallel to the flash lamps. It passes through the centre of the chamber, and emerges out the other side which is protected by three inches of lead shielding. If it is found that back scattering is serious at low energies, a "tunnel" type of absorber can be easily constructed.

A picture of the cloud chamber apparatus is shown in Plate 11, with the coils, camera, stand, mirrors, and a flash lamp. The control panel is to the right of the cloud chamber table. In the foreground is the lead shielding which houses the source and collimator. The overhead pipes carrying the
PLATE 11

CLOUD CHAMBER APPARATUS
cooling water for the magnet coils and chamber base are visible in the background.

The alignment of the source and functioning of the chamber were first extensively studied with 60 cm. of air in the chamber. The vapour used was two parts of ethyl alcohol to one part of water. Since no Xenon has been available to date, the operation of the chamber has been checked and preliminary pictures have been taken with Argon as the gas. The operation of the chamber should be quite similar, since both Xenon and Argon are monatomic gases. The Argon used was at 55 cm. pressure. An alcohol mixture of two parts of normal propyl alcohol to one part of water has been found to give good tracks. The Argon and alcohol were admitted into the chamber, using the procedure described under "Operation of the chamber".

b. Pictures

Plates 12 and 13 show the electrons obtained from the ThC beam filtered by a 1/4" plug of brass, with and without a magnetic field. Although there probably are several pairs in Plate 12, the great number of events makes their determination difficult. (In these and the following pictures, the negatives have not been "touched up", as is often done for publication purposes). Note the great number of Compton electrons knocked out of the chamber wall. There are approxi-
Plate 14

$H = 480 \text{ gauss}$

Plate 15

$H = 480 \text{ Gauss}$
mately as many diffuse as sharp tracks. This ratio is a function of the sensitive time of the chamber. If it is found that there are too many diffuse tracks formed in Xenon, there is provision in the control circuit for shuttering the source. (This will certainly be done with the (p,γ) radiation). There is a certain amount of background light in the chamber, internally reflected from the chamber walls, velvet, and top glass plate. This cannot be entirely eliminated with a chamber as small as the one used. The lamps must be correctly aligned to reduce the background as far as possible.

In order to cut down the radiation, the brass plug was replaced by a 3/4" lead plug. Plates 14 and 15 show the electrons obtained under these conditions. The great number of events has been considerably reduced. A typical pair is shown in the centre of the chamber, in Plate 14. This picture was taken with a magnetic field of 480 gauss across the chamber.

It will be necessary to have a thin window in the chamber wall to lessen the number of Compton electrons knocked out. This Beryllium foil will be best (not available to date). To test the effect of a window, the chamber was dismantled, and a half-inch hole was drilled in the plexiglass cylinder, to within 3/64" of the inside edge. The source was then lined
up with this window. Plate 16 shows a picture taken with a 3/4" filtering lead plug. The number of Comptons has been considerably reduced.

Plate 16

Electron Tracks. \( H = 480 \text{ gauss} \)
There has recently been renewed interest in the type of cloud chamber which is continuously sensitive. Besides being useful for providing an exceptionally vivid demonstration of charged particles, such a chamber would have obvious advantages which would make it extremely important as a research instrument. Very few moving parts would be required, so that mechanical difficulties would be greatly lessened. (See for instance, Section IV - 2). In addition, the elimination of the "dead time" of a conventional expansion chamber would allow the more rapid accumulation of data.

The first attempt to develop such a chamber was made by Vollrath in 1936, using chemical methods. Vollrath found that when HCl vapour and H₂O vapour were allowed to diffuse together, the mixture obtained was supersaturated with regard to both components. This sort of chamber was good for demonstration purposes only.

The type of continuously active chamber now being examined in several laboratories was first investigated by A. Langsdorf. This chamber attains a continuous supersaturation by the principle of diffusion of vapour through
Plate 17

TRAY OF WATER

CARDBOARD SATURATED
WITH METHANOL

BRASS PLATES

GLASS CYLINDER

DRY ICE

DIFFUSION CLOUD CHAMBER
a strong temperature gradient. Vapour evaporating from a warm surface will reach a region of supersaturation near a cold surface. Tracks will form along the paths of ionizing particles in this region.

I have briefly investigated this type of chamber for possible demonstration purposes. One model is shown in Plate 17. A brass plate 1/4" thick is placed on a block of dry ice. A piece of black velvet on this plate makes a good background for viewing tracks. A glass cylinder 6" in length and diameter forms the chamber proper. Packing cardboard soaked in methyl hydrate is placed on the cylinder, and another brass plate on this. A tray of warm water on the upper plate keeps it at room temperature. Under these conditions, there is a temperature gradient of 6°/cm. across the chamber.

Tracks from a polonium alpha source were observed by shining the beam of a projection lamp into the chamber, perpendicular to the observer's line of vision. For the first fifteen minutes a dense cloud of droplets formed, until a steady state was reached and all the dust particles were deposited. Then tracks were observed in a half-inch high region just above the bottom plate. It was found necessary to put an electric field of 1000 volts between the two plates, in order to increase the number of events. The
electric field helps remove some of the old ions which affect the background. Tracks formed continuously for about an hour, but throughout this period there was a background of droplets which would hamper photography. Any small leaks of air into the chamber caused turbulence and affected the tracks. "Frost" forming on the outside of the cylinder near the base had to be wiped away every few minutes, so that the tracks could be observed. A chamber of half the height (3") showed essentially the same characteristics.

It was hoped that a larger chamber would be less affected by convection currents from the walls. A plexiglass cylinder 12" high and 12" in diameter was constructed. However, no tracks could be obtained with this larger chamber, probably because it was not made very leak-tight.

The preliminary experiments indicate that it should not be too difficult to make a diffusion type chamber which can be used for demonstrations. The main requisites are that the chamber be leak-tight and that the temperature gradient be made uniform by using a fairly large chamber. Although all laboratories investigating the continuously active cloud chambers have had to cope with the same difficulties mentioned above, it seems certain that it will soon become a useful research instrument. Indeed, the nice tracks obtained by Cowan at the California Institute of Technology indicate that for many purposes, it may eventually supercede present day expansion chambers.
For the theory of pair production, I recommend the following references:


3. Jost, Luttinger and Slotnick, Phys. Rev. 80, 189, 1950

The last reference gives a recent treatment of the pair production process employing Feynman's method, which is equivalent to the Born Approximation.

The experimental work on pair production is covered thoroughly in the List of References. A good starting point for cloud chamber work is the article:

4. Das Gupta and Ghosh, Rev. Mod. Phys. 18, 225, 1946
LIST OF REFERENCES

1. Perrin, Comptes Rendus 197, 1100, 1933
2. Plesset and Oppenheimer, Phys. Rev. 44, 53, 1933
5. Jost, Luttinger, and Slotnick, Phys. Rev. 80, 189, 1950
8. Wheeler and Lamb, Phys. Rev. 55, 858, 1939
13. Watson, Phys. Rev. 72, 1060, 1947
15. Wentzel, Ann. d. Phys. 69, 335, 1922
23. de Benedetti, C. R. 200, 1389, 1935
27. Modesitt and Koch, Phys. Rev. 77, 175, 1950
29. Lawson, Phys. Rev. 75, 433, 1949
30. Powell, Hartsough and Hill, Phys. Rev. 81, 213, 1951
32. Wolfson, Phys. Rev. 78, 176, 1950
33. Tables of Electronic Functions, Federal Works Agency, W.P.A. for the City of New York, 1941
34. Ho Zah-Wei, Phys. Rev. 70, 224, 1946
35. Fowler and Lauritsen, Phys. Rev. 76, 314, 1949
36. Bethe, Phys. Rev. 69, 689, 1946
37. Bethe, Phys. Rev. 70, 821, 1946
40. Goudsmit and Saunderson, Phys. Rev. 58, 36, 1940
41. Moliere, Zeits. f. Naturforsch. 3a, 78, 1948
42. Snyder and Scott, Phys. Rev. 76, 220, 1949
43. Groetzinger, Berger and Ribe, Phys. Rev. 77, 584, 1950
44. Parry, M.A. Thesis, University of B.C., April 1949
45. Strong, Procedures in Experimental Physics, Prentice Hall, New York, 1949, p 171

47. Vollrath, R.S.I. 7, 409, 1936

48. Langsdorf, R.S.I. 10, 91, 1939

49. Needels and Nielson, R.S.I. 21, 976, 1950

50. Cowan, R.S.I. 21, 991, 1950

51. Fowler, Miller, Shutt and Thorndike, Phys. Rev. 81, 324, 1951

52. Nexson, Weddle and Nielson, Phys. Rev. 81, 325, 1951