Pair Production as a Means of Measuring the Energy of High-Energy Gamma Rays

A thesis presented to the Faculty of the Rice Institute in partial fulfilment of the requirements for the degree of Master of Arts.

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Section I: Historical Background

A: Pair Production

The positron, or positive electron, was discovered in 1932 by C. D. Anderson, in the course of cloud chamber studies of cosmic radiation. Anderson, using an unusually powerful magnet which produced a strong field over a large area, found a number of tracks which could only be interpreted as the paths of particles having a mass similar to that of the electron, but with positive charge. A positron track was often associated with an electron track, both tracks appearing to begin at the same point.

Shortly after Anderson's discovery, positrons were found to be produced when gamma rays of high energy fell on the heavier elements. Here too, electrons were found to be produced at the same time. In 1934 still another source of positrons was found—Curie and Joliot found that boron, magnesium, and aluminum became artificially radioactive after bombardment by alpha particles from polonium, emitting positrons for considerable periods after bombardment.

Further investigation has shown that pairs of positrons and electrons are produced when any element is bombarded with gamma rays of energy higher than 1.022 MeV, the energy corresponding to twice the rest mass of an electron. The number of positron-electron pairs is found to increase greatly with the atomic number Z of the element and with the energy of the gamma ray. In every case it has been shown the the sum of
the kinetic energies of each pair produced is equal to 1.022 MeV less than the energy $\hbar \nu$ of the gamma ray producing the pair, within the experimental error, or that the sum of the total energies of the particles, assuming that the rest masses are equal, is equal to the gamma ray energy.

There is no evidence to show that either the charge of the positron or the mass is different from that of the electron. Anderson found the specific ionization of the positron to be the same as that of an electron of the same energy to within the accuracy of measurement, about 20%. If the masses are assumed equal, this indicates that the charges are equal to within about 10%, since the specific ionization is known to be proportional to the square of the charge, other factors being equal. No direct measurement of the charge has been made, but the ratio of charge to mass for the positron has been compared directly with that of the electron and the two found to be equal within an experimental error of 2%. All other experimental results are consistent with the assumption that the charge and mass of the positron are identical in magnitude with those of the electron. The loss of energy of positrons in absorbing materials is found to be the same as for electrons of equal energy, though again the experimental knowledge is not complete.

Secondary gamma radiation of 0.5 MeV, with weaker radiation at 1.0 MeV, is found to be present whenever positrons are produced, with an intensity corresponding to the number of positrons produced. Since positrons are not known to exist in the free state for any appreciable length of time, it is
assumed that this gamma radiation represents "annihilation radiation" produced by the combination and coincident disappearance of a positron and an electron, the total energy of the two particles being radiated in the form of one or two gamma rays.

All of these experimental results can be explained on the basis of Dirac's relativistic electron theory. On this theory, the wave equation for electrons has solutions for both positive and negative values of kinetic energy. If $E$ is the total energy of an electron, it may take on values greater than $mc^2$ or less than $-mc^2$, but no intermediate values are possible. (Here $m$ represents the rest mass of an electron.) These negative energy values cannot be disregarded, since the theory gives a non-zero transition probability between the two states when perturbations are applied. In fact, a free electron with positive energy has an infinite transition probability of falling into a negative energy state with the emission of two quanta to conserve momentum. To avoid this difficulty Dirac assumed that all the negative energy states are usually occupied in the sense of Pauli, and postulated an infinite density of negative energy electrons throughout all space. The difficulties of this rather unsatisfactory hypothesis are mitigated by assuming that only deviations from this "normal" density are detectable; i.e. only positive energy electrons or unfilled negative energy states are experimentally detectable. Such an unfilled state, or "Dirac hole", would appear as a particle of positive energy and charge, since a particle of negative energy and charge would be missing; thus it would have all the properties of an ordinary particle. Dirac at
first assumed that these holes were protons, but finally had to discard this hypothesis because of the large mass and stable life of protons. Thus, as he wrote in 1931, the "hole", if it existed, would be a new particle unknown to experimental physics --the "anti-electron".

The positron, when discovered experimentally, was immediately identified with the Dirac hole, and all pair-production calculations advanced since have been based on Dirac's relativistic electron theory. On this theory the explanation of creation and annihilation of pairs is as follows:

A gamma ray of energy greater than 1.022 MeV may be absorbed by an electron of negative energy in a sort of photoelectric effect. This can take place only in the coulomb field of a third particle, such as a nucleus; the nucleus absorbs some momentum but practically no energy and allows conservation of energy and momentum. The negative energy electron has its total energy increased by more than $2mc^2$ and thus obtains positive kinetic energy. The unfulfilled negative energy state, representing the absence of an electron of total energy less than $-mc^2$, appears as a positron of total energy greater than $mc^2$, i.e. with positive kinetic energy. The sum of the total energies of the two particles appearing in place of the photon is thus equal to the original photon energy.

When the positron has been reduced to a fairly low velocity by interactions with other particles, there is a high probability that an electron will drop into the vacant state of negative energy, causing the disappearance of both positron and electron and the emission of the total energy of both in
the form of gamma radiation. If the process takes place in empty space two gamma rays of energy approximately 0.511 MEV will be emitted in opposite directions in order to conserve momentum. If the process occurs in the neighborhood of a nucleus, which can take up excess momentum, the total energy may be emitted in the form of a single gamma ray of approximately 1.022 MEV.

Using Dirac's theory, Bethe and Heitler have calculated the angular distribution of the ejected positrons and electrons. If θ is the angle of ejection with respect to the direction of the incident photon, the angular distribution of particles (electrons or positrons, each with total energy E) is given by:

\[ f(θ) = \frac{θ}{\left(\left(\frac{mc^2}{E}\right)^2 + θ^2\right)^2} \]

The general form of \( f(θ) \) is indicated in the figure above. It is easily shown that the angle of maximum probability approaches zero as the total particle energy E is increased, and hence as the gamma ray energy, of the order of 2E, is increased. For E=1.3 MEV, corresponding to the strong gamma ray emitted by ThC\(^{2+}\) of energy 2.62 MEV, a simple calculation shows that \( f(θ) \) reaches a maximum at \( θ = 12.8° \). This formula checks fairly well experimentally, though data is fairly meager.

Though the kinetic energy of a pair, equal to \( hν-1.022 \) MEV, may be distributed between the two particles in any possible way, the positrons will tend to have more energy, on the average, than the electrons, because the pairs are formed in the Coulomb field of a positively-charged nucleus. Bethe and Heitler, and later Jaeger and Hulme, have calculated the energy distribution.
They find the average difference in exergy proportional to $Z$, amounting to 0.28 MEV for pairs formed near lead nuclei by 2.62 MEV gamma rays. The number of particles ejected with nearly all or almost none of the kinetic energy of the pair is small compared to the total number of particles. Most of the positrons and electrons are ejected with energies close to half the maximum kinetic energy. The maxima of the energy distribution curves are not sharp; the curves tend to become rather flat for high energy gamma rays. The theoretical curves shown here are for 2.62 MEV gamma rays. Experimental data tends to bear out the theory, but again the evidence is not at all plentiful or highly accurate.

Bethe and Heitler have also calculated the cross section for pair production on the basis of the Dirac electron theory. They find that the cross section for pair production per nucleus is proportional to $Z^2$, but cannot be expressed as a simple function of energy. It is plotted as a curve in the figure below. The cross sections for the Compton effect for several elements are shown for comparison. The pair production cross section increases rapidly with $h\nu$ for $h\nu$ slightly larger than 1.022 MEV, then increases nearly as $\log h\nu$, and finally, for very large values of $h\nu$,
may approach an asymptotic value which may differ for different elements (after division by \(Z^2\)). The theory is believed not to be valid above approximately 70 MEV. The theoretical cross section agrees well with experiment, both as to the absolute number of pairs produced and as to dependence on energy and atomic number. Pair production is thus the predominant process for absorption of gamma rays at high energies. The energy for which it becomes predominant depends on the element in question, and is lower for larger \(Z\).


There are three principal means used at present to measure gamma ray energies less than 1 MEV, namely measurements of: the absorption coefficient of the rays in various materials, the energies of Compton electrons and photoelectrons produced by the rays, and diffraction of the gamma rays produced by crystals. All these methods have limitations, sometimes severe, and all become of less value for gamma rays of larger energies.

Crystal diffraction of gamma rays is an accurate method, but is useful only for strong sources and energies less than about 1 MEV. Absorption measurements are fairly reliable, provided that only one gamma ray is present. Measurement of the energies of the Compton electrons and photoelectrons is more reliable than absorption measurements and is perhaps the most widely used method, especially at higher energies. Magnetic focusing of these ejected electrons is the most usual method, with counters giving more accurate results than cloud chamber
measurements. The use of thin foils as targets minimizes line-broadening effects due to straggling of the electrons, but cuts down the yield of electrons, necessitating a stronger source. For this reason fairly thick targets are usually used. Measurement of the photoelectron energy gives better resolution of gamma ray energies than measurement of the energy of Compton electrons, since photoelectrons possess sharply defined values of energy depending only on the gamma ray energy and the electron energy levels in the atomic structure of the target, while the energy of the Compton electrons varies with the angle between the incident gamma ray and the ejected particle. Thus Compton electrons have energies varying over a wide range, the exact distribution depending on the geometry of the experiment. Only the high energy end point of the distribution is of value in determining the gamma ray energy, and this end point is always somewhat uncertain.

For these reasons the photoelectric process is made use of in preference to the Compton process at low energies. However, the photoelectric process has a much smaller cross section than the Compton process for energies above 1 MeV. It becomes very difficult to detect photoelectrons above the Compton background at these higher energies. Hence most of the information about higher gamma ray energies has been gathered from observation on Compton electrons. The Compton cross section decreases roughly as \( \frac{1}{E^2} \) at high energies, making measurements of gamma ray energies by this means still more uncertain. Thus the difficulties of accurate gamma ray energy measurement increase as the energy increases.
Since the cross section for pair production increases rapidly above 1 MEV, it is possible to make use of this process in the measurement of higher gamma ray energies. Measurements of the energies of pairs produced in the gas of a cloud chamber have given some information on the energy of these gamma rays, but the accuracy of the results is limited by the large number of photographs needed to reduce the statistical error to a reasonable value. A double spectrograph for secondary electrons and positrons, with means for recording coincidences when an electron and a positron of nearly equal energy are ejected simultaneously and pass through counters on opposite sides of the spectrograph, might be a valuable means of measuring high gamma ray energies. The use of several counters on each side would nearly eliminate background counts due to gamma radiation and other causes; a coincidence curve plotted as a function of particle energy should show a well defined maximum at an energy corresponding to \( \frac{h\nu - 1.021}{2} \) MEV. The gamma ray energy could be determined from the position of this maximum. This method would thus have the advantage which the photoelectric method has at lower energies in depending on the maximum in a curve instead of an uncertain end point, with consequently better resolution. As far as is known, no such use of a double spectrograph is recorded in the literature, so that its value has not been determined.
Section II: Purpose of the Experiment.

The purpose of the present experiment is to determine the value of such a double spectrograph in the measurement of high gamma ray energies. An apparatus for this purpose was designed by G. E. Mandeville, now on leave of absence from the Rice Institute, and was constructed by J. F. van der Henst and P. deVries, instrument makers for the Rice Institute Physics Department. Experiments to determine the usefulness of the spectrograph have been undertaken by the writer, with the initial assistance of I. E. Slawson.

Section III: Description of Apparatus.

The principal piece of apparatus is the double magnetic spectrograph, which is placed between the poles of a large Weiss electromagnet. The spectrograph, or magnet box, is shown in cross section view in Figure 1. The energies of secondary electrons and positrons ejected from a "radiator" by gamma rays are measured by semicircular focusing in a uniform magnetic field. The focal points for electrons and for positrons are on opposite sides of the magnet box, with two counters on each side so placed that an electron or positron must follow a circular path of radius 5.50 cm from the radiator in order to pass through two counters. The counters and the entire magnet box are filled with a mixture of argon and alcohol with partial pressures respectively 9 cm and 1 cm of mercury. This gas, present throughout the box, will slow down and scatter appreciably particles of low
energy, but the effects should not be noticeable for electrons and positrons with energies higher than perhaps 0.4 MeV. Since all four counters are open to the interior of the magnet box, there is no matter present aside from the gas to slow down or absorb particles following the desired paths.

Radioactive material, if used as a source of gamma rays, is placed in a small aluminum cup which forms part of the outside wall of the magnet box. The bottom of this cup is a sheet of aluminum 0.5 mm in thickness which serves as a radiator of secondary particles. In order to increase the yield of pairs a thin lead radiator may be attached to the aluminum radiator, on the interior of the magnet box.

Lead blocks are placed so as to shield all four counters from gamma radiation so far as possible. The two blocks used are 7.8 cm thick along the direct paths between the radioactive material and the counters. Gamma radiation still accounts for large backgrounds in all the counters, but it would not be possible to interpose much more lead while using the present magnet and pole pieces, as this would necessitate a larger value of the path radius $r$.

A system of defining slits allows only particles within a certain energy range to reach the counters. The narrowest slits, placed at the two focal points, are 3.0 mm wide; the sides of these slits are brass strips 2 cm long, 1 cm wide, and approximately 0.32 cm thick. The counters which are shielded by these slits are set in blocks of lucite which give additional shielding. The counters are 2.0 cm long with diameters of 1.0 and 1.5 cm. The two smaller counters are
placed next to the brass slits, the larger counters adjacent to the smaller counters and further away from these slits; the varying diameters allow for spreading of the beam of particles after passing through the brass slits. The other defining slits, consisting of the two lead blocks and five blocks of aluminum, are so placed that, although the maximum number of counts will be recorded for particles with path radii of 5.50 cm, particles with r varying between 4.3 and 6.1 cm may also be counted. Thus $r=5.50 \pm 0.60$ cm; with the magnetic field $H$ set for any given value, particles with $Hr$ varying from the desired value by as much as 11% in either direction will be admitted to some extent. This spread in $Hr$ is of course undesirable from most standpoints, but decreasing the spread would mean cutting down the number of particles reaching the counters by the same factor, and hence decreasing the statistical accuracy obtainable by counting for a given length of time. Thus it is of importance that the spread in $Hr$ be not too small.

The high DC voltage necessary to operate the counters is furnished by a half-wave rectifier, with the output continuously variable from 0 to 1800 volts by means of a variac in the primary circuit of the plate transformer. The AC input to the variac is regulated by a Keleket voltage regulator, which also regulates all the voltages used in the amplifiers. The voltages applied to the counters may be varied individually by means of a one megohm voltage dividing circuit placed across the high voltage output. The load on the high voltage supply consists almost solely of this voltage divider; thus there
should be no voltage fluctuations due to variation of load. The time constant of the high voltage circuit is about two seconds, indicating about 0.3% ripple voltage in the DC supply. The counters are found to operate in the neighborhood of 1000 volts, with approximately 30 volts between the beginning of the proportional region and the end of the Geiger region.

In order to register coincidences, a four-channel amplifier and Rossi circuit was designed and built. A two-stage preliminary amplifier is necessary for each counter because of the small size of the voltage pulses obtained directly from the counters; the amplified pulses are fed into a conventional Rossi circuit, the output from which goes to a final stage which furnishes current to a mechanical recorder. Provision is made for opening the plate circuits of any of the four tubes in the Rossi circuit, so that the output of any one counter or coincidences between any combination of counters may be recorded.

The pole pieces are of soft iron, roughly semicircular in shape, about 2.5 cm thick, and slightly smaller than the outside dimensions of the magnet box. The magnetic field strength was measured at various points between the pole pieces for various field currents, using a Cenco fluxmeter and a small snatch coil. This was done without the magnet box between the poles, but the presence of the box should not affect the field since there are no ferromagnetic materials in the magnet box. A curve was plotted for magnetic field strength as a function of current for the point midway between
the centers of the pole pieces, from which the value of the magnetic field could be read for any value of current. The fluxmeter was calibrated by comparison with a Cenco line-turn standard. It is thought that the probable error of the measured field strength is less than 1%. Higher accuracy could be obtained by the use of a snatch coil with more turns so as to give larger deflections on the fluxmeter.

It was found that the field strength was largest between the centers of the pole faces. Near the edges of the pole faces, beyond the paths of electrons and positrons in the magnet box, the field dropped off about 2% from the maximum value. Thus the field appeared to be sufficiently uniform for the purposes of this experiment. The maximum field obtained was 4150 gauss with a current of 19.50 amperes. This corresponds to \( Hr = 2.28 \times 10^6 \) gauss-cm, or an electron energy of 6.3 MeV; thus a gamma ray of energy 13.6 MeV should be measurable with this apparatus. Higher values of field strength could be obtained, though it would be difficult to maintain a larger field for any considerable time, because of heavy drain on the Edison cells supplying the field current. No means has been provided for the regulation of the DC voltage supplying the field current. The voltage holds steady to within about 1% for considerable periods, provided that the current drain is not large. If the supply voltage changes slowly, the current can be maintained at a nearly constant value by rheostat changes.
Section III: Experimental Results

The resolving time of the amplifier and Rossi circuits may be defined as the smallest time interval by which two pulses from different counters which do not register a coincidence may be separated. If two counters are operating with counting rates of $n_1$ and $n_2$ counts per second, and the counting rates are low enough so that the counters are in a state of discharge for a relatively small portion of the time, then the number of accidental coincidences registered per second is given by $A$ in the formula: $A = 2n_1n_2t$. Here $t$ is the resolving time in seconds; it is assumed that there are no real coincidences between the two counters. Similarly, for the case of $m$ counters, $A = mn_1n_2 \ldots n_m t^{m-1}$. It is of course desirable that the resolving time $t$ be small, in order to obtain the smallest possible rate of accidental coincidences.

The resolving time of the circuits used in this experiment was determined under various conditions, using gamma rays from radium as a source of counts. The resolving time was found to depend on the size of the pulse which reached the Rossi circuit; thus, for any given pulse size from the counters, minimum resolving time would be obtained by minimum setting of the gain controls in the amplifier stages, consistent with proper operation. For the coincidence counts which will be discussed in this paper the resolving time was of the order of $10^{-4}$ seconds.

However, it was found that coincidence rates between adjacent counters—that is, between two counters on the same side of the magnet box—were much higher than coincidences
between any other combination of two counters. It was also found that the counting rate of any counter was increased when the adjacent counter was put into operation. This was found to have no connection with the amplifier, and no way could be discovered in which external coupling might occur between adjacent pairs of counters and not between other combinations. Thus the effect seemed to be internal; some coupling apparently occurred between adjacent counters due to the fact that nothing separated the sensitive volume of any counter from the sensitive volume of the adjacent counter. Assuming that the increase in counts when both counters are operated represents counts that spread from one counter into another, causing a coincidence, the coincidence rate between adjacent counters should be equal to the sum of the increases caused in the counting rates of each by the operation of the other. (The expected accidental rate, without coupling between counters, is negligible in comparison with the observed coincidence rate in these cases.) This relation was found to hold true in all cases. As an example, the counting rates of two adjacent counters, designated #1 and #2, were taken when operating alone (designated by 1(-) and 2(-)) and when both counters were in operation (designated by 1(2) and 2(1)), and the coincidence rate between 1 and 2 (designated by: 1&2) was observed, using gamma rays from radium to furnish counts. There should be no appreciable rate of real coincidences (without coupling) in this case, as there was no magnetic field.
The data found is tabulated here:

<table>
<thead>
<tr>
<th>Counter</th>
<th>Counts per second</th>
</tr>
</thead>
<tbody>
<tr>
<td>1(2)</td>
<td>2.36</td>
</tr>
<tr>
<td>1(-)</td>
<td>1.35</td>
</tr>
<tr>
<td></td>
<td>1(2) - 1(-) = 1.01</td>
</tr>
<tr>
<td>2(1)</td>
<td>3.05</td>
</tr>
<tr>
<td>2(-)</td>
<td>1.94</td>
</tr>
<tr>
<td></td>
<td>2(1) - 2(-) = 1.11</td>
</tr>
<tr>
<td>1&amp;2</td>
<td>2.19</td>
</tr>
<tr>
<td></td>
<td>Sum of increases = 2.12</td>
</tr>
</tbody>
</table>

Thus the sum of the increases (2.12) is equal to the coincidence rate (2.19) to within the statistical error involved. It would appear that in this case about 50% of the discharges in #2 spread to #1, and about 30% of the discharges in #1 spread to #2. (#1 is the smaller counter.)

The high coincidence rates found between adjacent counters, comparable to the rates in the individual counters, meant that no appreciable advantage would be obtained by using four counters instead of two (one on each side). The background rates would be nearly the same in the two cases; this was found to be correct. Therefore the experimental results to be described were obtained using only two counters, the two smaller counters directly behind the brass slits.

As a source of gamma rays, one milligram of radium, encased in a small metal cylinder, was placed on the center of the aluminum radiator—that is, the bottom of the aluminum cup—with the axis of the cylinder parallel to the magnetic field, and hence to the slits and counter axes. Counting rates were observed for the two counters used, both individually and in coincidence; the runs for individual counters
were one minute long and the coincidence runs were for two minutes. The results obtained for various values of Hr are shown on Graph 1. Counters \#1 and \#4 counted positrons and electrons, respectively, in addition to large gamma ray backgrounds. The counting rate for \#1 was found to be approximately constant for all values of magnetic field used; no variation from an average value of about 520 counts per minute was found that could not be accounted for as statistical error. The counting rate for positrons was thus entirely obscured by the gamma ray background. The counting rate of \#4 showed large variations with field, rising to a double peak and dropping back to the background rate as Hr increased; in this case the rate of electron counting was evidently larger than the gamma ray background. The coincidence rate also varied considerably with the magnetic field. Such a result would be expected even if no real coincidences were observed, since the accidental rate is proportional to the product of the counting rates in the two counters, and this product varied by a factor of approximately 2.5, as is seen from the graph. However, the variation in the coincidence rate was found to be somewhat larger than would be expected from accidental counts, so that apparently a small counting rate for pairs was observed. A second series of determinations was made under the same conditions, with the field varied in smaller steps. Counting rates were observed for electrons and for pairs only; all counting rates were determined for periods of one minute. The curves obtained were of the same form as in the first case and are shown in Graph 2; no new
facts were uncovered. The secondary electron spectrum is of the general form to be expected from radium. The maximum energy observed for secondary electrons in these experiments is about 2.2 MEV, corresponding to $H_0=9000$ gauss-cm. The gamma ray of highest energy emitted by radium is of 2.2 MEV energy (RaC), and photoelectrons would be ejected with this energy from a radiator. However, most of the electrons observed are undoubtedly Compton electrons, with energies varying over a wide range. No detailed analysis of the electron spectrum is possible from these results, because of the lack of resolution of the spectrograph; moreover, the gamma-ray spectrum of radium is very complex.

In order to increase the yield of pairs, a thin lead sheet (0.014 cm thick) was attached to the aluminum radiator, on the inside of the magnet box. Counting rates were again determined for counters #1 and #4 both singly and in coincidence; the results are shown in Graph 3. All runs were for periods of one minute, except for the coincidence runs from $H_0=0$ to 1023, which were taken for periods ranging from 11 to 19 minutes. Thus the statistical error on these four points is much smaller than for the other coincidence points. Similar determinations would have been made for other values of $H_0$ in a second run, except that serious leaks developed in the apparatus at this time and brought operations to a halt.

In order to determine the momentum distribution of the pairs formed in lead, several corrections must be applied to the coincidence rates shown in Graph 3. These values have been replotted in Graph 4, on a larger scale, and a smooth
curve has been drawn between the points, in the hope that statistical errors have thus been reduced. The counting rate for no field appears to be the same as the counting rate for large fields, and is assumed to be due to accidental counts only; thus we assign a definite value to the resolving time, which may be calculated to be 250 microseconds in this case. Using this value of $t$ and the known counting rates of $\#1$ and $\#4$ for the range of $Hr$ we are concerned with, the expected rate of accidental counts has also been plotted in Graph 4. It coincides with the observed coincidence rate at both end points—since we assumed that it did—but falls a considerable distance under the curve along the intermediate range. The difference between the observed coincidence rate and the expected accidental rate may be assumed to be the counting rate for pairs. In order to obtain the true momentum distribution of the pairs, we must divide the counting rate by $Hr$. This compensates for the fact that the range of momenta (momentum is proportional to $Hr$) through which a pair may be counted for a given value of $Hr$ is approximately $22\%$ in this spectrograph, as previously discussed; thus the spread in $Hr$ is proportional in absolute value to $Hr$. The distance between the two smooth curves discussed so far has been divided by $Hr$; the resulting curve is also plotted in Graph 4 and is seen to reach a definite peak at a point corresponding roughly to $Hr=1700$, or a particle energy of about $0.2$ MEV. This indicates an average gamma ray energy of $1.4$ MEV, possibly what would be expected from the complex spectrum of radium. However, such low energy electrons and positrons have a large
probability of scattering in the gas present in the spectrograph. Such scattering could also account for the tail of the curve at higher energies, though this may be due only to statistical error.

The gamma rays of highest energy emitted by radium are at 1.8 and 2.2 MeV, the lower energy component being about three times as intense as the other. These should produce pairs with average particle energies of 0.4 and 0.6 MeV respectively. These points, indicated on the momentum distribution curve, are relatively close to the peak. Since it is not expected that these energies would be resolved by the spectrograph in its present form, and since statistical error introduces uncertainties into the exact shape of the coincidence curve, the results obtained are of the expected type.

Section IV: Conclusions.

It would appear that pairs have been detected in the spectrograph, and the energy of the particles is approximately what is to be expected. The complex gamma ray spectrum of radium makes interpretation of results difficult. Moreover, the spectrograph is not intended to be of great value at these fairly low energies. A better check could be made with a substance emitting a single strong gamma ray of fairly high energy, such as ThC\textsuperscript{226} (2.62 MeV) or Na\textsuperscript{24} (1.4 and 2.8 MeV). An important improvement in results could be obtained by eliminating the spread of discharges between adjacent counters, so that all four counters could be used in coincidence. Possibly thin metallic foils placed between adjacent counters would produce this result without appreciable
absorption of particles. In this case the large gamma ray background could be almost eliminated by coincidence counting, and much more accurate results would be possible.

The accuracy with which this spectrograph can measure the energy of high energy gamma rays is still uncertain, the gamma rays of radium being of relatively low energy. It appears probable, however, that the spectrograph will be of value when improved in certain respects; it may be possible to narrow the slits for better resolution once the accidental background has been largely eliminated.

The writer wishes to express his appreciation for the guidance of Professors H. A. Wilson, T. W. Bonner, and J. R. Risser, and for the assistance of I. E. Slawson, J. F. van der Henst, and P. deVries in this experimental work.
GRAPH 2

SOURCE: Radium
Radiator: Aluminum

# 4 COUNTER

2.2 MEV

Counts per minute

COINCIDENCES

HP (emu-cm)

Counts/Min

0 1 2 3 4 5 6 7 8 9 10 11 12 13 14,000
Source: Radium
Radiator: Lead

Graph 3

Counts per minute vs. Hp (emu cm)

#4 Counter

He1 Counter

2.2 MeV

Coincidences

Counts/Min

0 1 2 3 4 5 6 7 8 9 10 11 12 13 14,000
Graph

Source: Radium
Radiator: Lead

Momentum Distribution for Pairs

Counts per Minute

\[
\frac{N - A}{H_P}
\]

0.2 MeV

0.4 MeV

0.6 MeV

Coincidences (N)

Expected Accidental Rate (A)

\[0 \quad 1 \quad 2 \quad 3 \quad 4 \quad 5 \quad 6 \quad 7 \quad 8 \quad 9 \quad 10 \quad 11 \quad 12 \quad 13 \quad 14,000\]

\[0 \quad 5 \quad 10 \quad 15 \quad 20 \quad 25 \quad 30 \quad 35 \quad 40 \quad 45 \quad 50\]
Bibliography

8. J. D. Stranathan, The Particles of Modern Physics (Blakiston, 1942), 377.
12. F. Rasetti, Elements of Nuclear Physics (Prentice-Hall, 1936), 92.

Note: A more complete guide to the literature on positrons will be found in J. D. Stranathan, The Particles of Modern Physics, Chapter IX.