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UMI
GAMMA RAYS FROM BERYLLIUM
BOMBARDED WITH ALPHA PARTICLES AND
FROM BORON BOMBARDED WITH DEUTERONS

A Thesis
Presented to
the Faculty of Rice Institute

In Partial Fulfillment
of the Requirements for the Degree
Doctor of Philosophy

by
James Terrell
Houston, Texas
May, 1950

Approved

[Signature]
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CHAPTER I

PAIR PRODUCTION AS A MEANS OF MEASURING HIGH GAMMA RAY ENERGIES

The gamma rays produced in the transmutation of light nuclei give important clues to the energy levels in these nuclei. We shall not consider here, of course, the x-rays which come from radiative loss of energy by fast electrons in matter and from transitions between atomic energy levels, or the 0.511 Mev radiation from positron annihilation. Other types of high energy radiation come either from transitions between energy levels of the product nuclei (usually between an excited level and the ground level) or from transitions in the compound nucleus between the initial excitation level and a lower level, usually the ground level. Transitions in the compound nucleus are called capture gamma rays, since no particle has managed to escape before the emission of a gamma ray. In the case of capture gamma rays the gamma ray energy varies with the bombarding energy throughout the range of bombarding energy which produces it, since the gamma ray energy is the difference between the varying excitation energy and a fixed energy level in the same nucleus. Non-capture gamma rays have energies independent of the bombarding energy because the levels involved are in the product nucleus. Variation of excitation energy of the compound nucleus in this case produces a variation in energy of the particle which is emitted in the transition to the product nucleus; the gamma ray energy remains constant. A slightly different case occurs when the product
nucleus is a beta-emitter; in this case gamma radiation may be given out in the transition from the beta-emitter to the final (third) nucleus; the gamma rays then represent transitions between energy levels in the final nucleus, not in the beta-emitter.

In general, except for capture gamma rays, the energy of a gamma ray is sharp and well defined, since gamma radiation is usually a much slower process than particle emission. The initial energy level is thus necessarily a narrow one, and so is the final level, except in the case in which the final level lies above the dissociation energy of the nucleus and heavy particle emission occurs following the gamma ray.

There are various ways of measuring the energy of gamma rays, applicable to different energy ranges. For energies of the order of 1 Mev or lower, the energies of Compton electrons or photoelectrons ejected by the gamma rays may be measured fairly easily. The energies of the Compton electrons depend on the angle of scattering of the gamma ray, so that the measurements on photoelectrons, both internally and externally converted, give more accurate energy values. The most accurate energy measurements in this range have been made with a curved crystal spectrometer in which diffraction of gamma rays by the crystal lattice is utilized. This method becomes progressively more difficult as the gamma ray energy increases, because of the very small angles involved. Measurements of photoelectron energies, the next most accurate means, also become less practical as the gamma ray energy increases because of the rapid decrease in cross section for this process with increasing energy above 1 Mev. The photoelectron spectrum also tends to be obscured by the Compton electron
spectrum, since this does not decrease so rapidly with energy. The
Compton electron measurements are quite useful over a wide range of
energy, though their yield is low when the energy is as high as 5 to
10 Mev.

Probably the best way of measuring high gamma ray energies,
in the range higher than 3 or 4 Mev, is through observation of electron-
positron pairs. The production of pairs in the field of a nucleus becomes
energetically possible when the gamma ray energy is greater than 1.02 Mev,
the rest mass energy of the two particles. Above this threshold the pair
production cross-section, as calculated theoretically by Bethe and Heit-
ler, (Be34) rises at first slowly and then, above 3 Mev, rapidly and al-
most linearly with energy. It becomes larger than the Compton cross
section in lead above 5 Mev, and in aluminum above 15 Mev. The theory
is not expected to be valid above approximately 70 Mev (137 mc^2). The
cross section per atom is proportional to Z^2 at all energies less than
30 or 40 Mev; at higher energies ( E > 137/Z^3/2 Mev) the effects of
screening of the nuclear Coulomb field by atomic electrons begin to
become apparent. Screening causes the ratio of heavy element cross
sections to light element cross sections to be less than the square of
the ratio of nuclear charges.

The total energy k of the gamma quantum is given to the two
particles produced, so that the sum of their kinetic energies is 1.02
Mev less than the gamma ray energy, the rest masses accounting for the
rest of the energy. All the possible ways of distributing the energy
have nearly equal probability in the energy range covered by the experi-
ments to be described in this thesis (2 to 15 Mev). However, it is improbable that one particle will have practically all the energy, and the condition of maximum probability (a very flat maximum) is that of equal distribution of energy. This is a consequence of the Born approximation used by Bethe and Heitler. Calculations by Jaeger and Hulme (Ja36) show that the positron, on the average, has slightly more kinetic energy than the electron, because of the Coulomb forces between the nucleus and the pair particles. This consideration shifts the location of the flat maximum in the energy distribution slightly. The probabilities for various energy distributions, except for the extremes, are so nearly equal that the total cross section for pair production is roughly equal to 80% of what it would be if all modes of energy distribution had the same probability as that of equal energy distribution, in the range 2 to 10 Mev. The actual ratios are: \( \frac{\sigma}{\sigma_{\gamma_2}} \) is the ratio mentioned above)

<table>
<thead>
<tr>
<th>Gamma Ray Energy (Mev)</th>
<th>1.53</th>
<th>2.04</th>
<th>3.06</th>
<th>5.11</th>
<th>10.22</th>
<th>25.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ratio, ( \frac{\sigma}{\sigma_{\gamma_2}} )</td>
<td>0.785</td>
<td>0.785</td>
<td>0.787</td>
<td>0.819</td>
<td>0.859</td>
<td>0.916</td>
</tr>
</tbody>
</table>

The angular distribution of the particles is extremely complicated, and has not been worked out explicitly except for very high energies. The complication is primarily that of the interdependence of the angular distributions for electrons and for positrons. Thus, in addition to the angular distributions for each of the two particles, the angular distribution of the vector sum of their momenta must also be considered. This correlation makes any calculations involving angular distributions of pair particles quite complicated, if accuracy is desired. It has been
shown (Be34) that the angular distribution of either component of the pair, considered independently is given approximately by

\[ f = \frac{\theta \, d\theta}{[(m_0 c^2/E)^2 + \theta^2]^2} \]

where \( E \) is the total energy of the particle, including its rest energy, \( m_0 c^2 \) is the rest energy of the electron, and \( f \) is the fraction of particles whose paths make an angle of \( \theta \) to \( \theta + d\theta \) with the quantum direction. Integrating this approximate distribution, we find that the fraction of particles whose paths lie within the angle \( \theta \) is given by

\[ F(\theta) = \frac{\theta^2}{[(m_0 c^2/E)^2 + \theta^2]} \]

Thus \( m_0 c^2/E \) is a characteristic angle of pair production, within which half of the path directions lie.

All of these theoretical calculations have been verified experimentally in an approximate way. A nearly complete set of references to the important literature on pair phenomena before 1942 is given by Stranathan. (St42) Perhaps the most accurately verified quantity is the pair cross section for various energies and materials. However, much remains to be done in this matter.

The predominance of pair production over the Compton and photo-electron processes at high energies makes pair measurements the logical means of measuring high gamma ray energies. The gamma ray energy is found, of course, by measuring the energies of both members of a pair and adding to their sum the rest mass energy of 1.02 Mev. Numerous cloud chamber measurements have been made on gamma ray spectra as indicated
by pair energies. A few pair spectrometers using counters had been built and reported on before 1947. Possibly the earliest reported was that of Dzelepow, (Dz39) in 1939, which was used to measure the gamma ray spectrum from a Polonium-Beryllium source. In 1941 Tomlinson (To41) reported on a pair spectrograph which was used on the nuclear pairs from $^{16}\text{O}$.

Since 1947 the number of pair spectrometers in use has increased fairly rapidly. They have been used on the gamma ray spectra from light nuclei under proton bombardment, (Wa48) on the capture gamma ray spectra due to slow neutrons, (Ki50) and on the x-ray spectra from large accelerators. (La49)
CHAPTER II

HISTORY OF THE GAMMA RAY SPECTRA FROM BERYLLIUM BOMBARDED WITH
ALPHA-PARTICLES AND FROM BORON BOMBARDED WITH DEUTERONS:

The nuclear reaction \( \text{Be}^9 (\alpha, n)\text{C}^{12}, (q=5.75 \text{ Mev}) \), has long
been a well known source of neutrons. A study of the penetrating
radiation produced when the 5.3 Mev alpha particles from polonium
were allowed to strike a target of beryllium led Chadwick (Ch32) to
the discovery of the neutron. Though many investigators have used the
neutrons from this reaction to study other nuclear reactions, the
gamma ray spectrum given by this neutron source has never been determined
with any great accuracy. The earlier investigators were unable to
obtain polonium-beryllium sources of any great strength; furthermore,
the presence of the neutrons is a complicating factor.

Bothe (Bo36a) reported the results of an investigation into
this gamma ray spectrum with a 180\(^\circ\) -focussing electron spectrometer.
From determinations of the secondary electron and position spectra
produced in aluminum and lead radiators by a 30 millicurie source,
he deduced the presence of three gamma rays, of energies 2.7, 4.2,
and 6.7 Mev, and more or less equal intensity. Statistical fluctuations
in the data are not unimportant, however due to a large background, and
the resolution was somewhat low, so that the presence of three gamma
ray lines does not seem to be established with finality by this data.

Maier-Leibnitz, (Ma36) investigated neutron-gamma and gamma-
gamma coincidences due to this source, and concluded that the neutrons
and the gamma rays, as well as the 2.7 and 4.2 Mev gamma rays, were simultaneous. From this Maier-Leibnitz concluded that these two gamma rays are the product of a cascade transition from the 6.7 Mev level which is also the source of the highest energy gamma ray. Counting rates were necessarily very low in this work, and statistical fluctuations of corresponding importance.

A second investigation of the gamma ray energy spectrum was performed by Dzelepow (Dz39) by means of a simple pair spectrometer, using 180° focussing and two counters in coincidence on opposite sides of the source. His spectrometer had the unusual feature of accepting particles which left the source in two exactly opposite directions, so that the counters received particles from nearly every direction, instead of merely from one side. The number of coincidences obtained with a polonium-beryllium source surrounded by lead foil varied from 0.5 to 4.0 per hour, depending on the magnetic field; the coincidences obtained with no source were of the order of 0.5 per hour. Dzelepow concluded that the spectrum obtained showed the presence of gamma rays of energy 2.7, 4.7, and 7.0 Mev, with the middle line fourteen times as strong as the high energy line. The intensity of the lower line was not estimated because of unfavorable conditions for detecting it, but it produced only a small peak compared to the 4.7 Mev gamma ray. The number of counts represented by each point on the curve is so low that the two weak peaks might be interpreted as statistical fluctuations, with no great improbability.

Szalay and Zimonyi, (Sz40) using a 30 millicurie polonium source,
studied the production of gamma rays as a function of alpha particle energy in the range 0-5.3 Mev. They varied the energy of the alpha particles by varying the pressure of the air between the polonium and the beryllium. They observed an apparent threshold in gamma ray production for 1.62 Mev alpha particles, with a smooth, non-resonant rise above this energy. They concluded that the nuclear reaction was primarily a transition from a continuum in C^{13} (the compound nucleus) to the 6.7 Mev level in C^{12} which had been found by other investigators (see above). This conclusion does not seem to be proved by the yield curve, which closely resembles a penetrability curve and has no sharp threshold, as far as statistical considerations allow us to judge.

Szalay and Zimonyi did not measure the absolute yield of these gamma rays, but accepted the figure determined earlier by Bothe and Becker: (Bo30) $34.0 \pm 0.7 \times 10^{-6}$ quanta per alpha particle of 5.3 Mev energy incident on a thick beryllium target. This compares with a thick target yield of neutrons measured variously as $50 \times 10^{-6}$, $73 \times 10^{-6}$, and $77 \times 10^{-6}$ neutrons per polonium alpha particle.

Slatin (Sl48) obtained an excitation curve for the gamma radiation from this reaction, similar to the data of Szalay and Zimonyi, with a rapid rise in yield beginning at about 1.7 Mev alpha energy. There was no sharp threshold, but rather a Gamow penetration type of yield. Neutron emission appeared to follow the same curve. Slatin lists other work which has produced essentially the same results, by Webster, by Rasetti, and by Curie and Joliot.

The neutron spectrum from polonium beryllium (thick target) was investigated by Richards, Speck, and Perlman, (Ri46) who measured
recoil proton tracks in emulsions. They found a broad maximum at about 2 to 3 Mev (neutron energy), with the high energy end extending beyond 10 Mev (a few neutrons) and the average energy greater than 4 Mev. This data might be interpreted as indicating a level in C\textsuperscript{12} around 7 Mev. However, the significance of the data is somewhat obscure as the neutrons were emitted at all angles with respect to the bombarding alphas, and the alphas were of course not monochromatic in a thick target.

Earlier work on the neutron spectrum by Bernadini and Bocciarelli (Be36) indicated levels in C\textsuperscript{12} at 3.0, 4.4, and 6.4. Blau (Bl34) reported levels at 6.5, 4.7, and less than 1.7. However, recent careful work by Bradford and Bennett, (Br50) using a thick target and 1.4 Mev alpha particles from an electrostatic accelerator, and measuring the range of the recoil protons in Ilford C-2 plates, has shown very definitely the presence of two well-resolved neutron groups, indicating transitions to the ground state of C\textsuperscript{12} and to an excited level at 4.45 Mev. No evidence was found of any 3 Mev level in C\textsuperscript{12}. A level at 7 Mev would not have been excited at this bombarding energy.

A study of the literature indicates, then, that there is a fair amount of uncertainty as to the neutron and gamma ray spectra from a polonium-beryllium source, and hence as to the levels in C\textsuperscript{12} so far as this reaction involves them.

Another important reaction having a direct bearing on these levels is that of B\textsuperscript{11}(d, n)C\textsuperscript{12}, with Q = 13.78 Mev.

The gamma rays from the bombardment of natural boron (18.8% B\textsuperscript{10})
with deuterons were reported by Gaerttner, Fowler, and Lauritsen (Ga39) to have energies of 1.5, 2.2 ± 0.3, 4.4 ± 0.3, 6.9 ± 0.4, and 9.1 ± 0.4 Mev. The relative intensities, with the accelerator at 550 to 850 kev peak voltage, using a thick target, were > 2.5, ~ 2.5, 1.0, 0.3, and 0.1 respectively. The energy measurements were made on pairs and recoil electrons in a cloud chamber.

These results have been confirmed by Halpern and Crane (Ha39) who bombarded a thick natural boron target with deuterons of 700 kev maximum energy and observed secondary electrons in a cloud chamber. They found gamma ray energies of 1.4, 2.4, 4.2, 6.0, and 9.1 Mev, with relative intensities of 1,1,6,2, and 1. There are a number of reactions which might account for these gamma rays, particularly because of the presence of both isotopes of boron. It has been generally thought (Ho48) that the two or three gamma rays of highest energy come from the $\text{B}^{11}(\text{d},\text{n})\text{C}^{12}$ reaction, because of the levels in $\text{C}^{12}$ which are believed to be located at 4.3, 7.1, and 9.5 Mev.

The neutron groups from deuteron bombardment of unseparated boron were observed by Bonner and Brubaker. (Bo36) The Q values found were 13.4, 9.0, 6.0, and 3.9 Mev. Bonner and Brubaker assigned the two higher energy groups to the reaction $\text{B}^{11}(\text{d},\text{n})\text{C}^{12}$, the transitions being to the ground state of $\text{C}^{12}$ and to an excited level at 4.4 Mev. The two lower energy groups were assigned to the $\text{B}^{10}(\text{d},\text{n})\text{C}^{11}$ reaction (levels in $\text{C}^{11}$: ground state and 2.1 Mev). If all groups had been assigned to the reaction $\text{B}^{11}(\text{d},\text{n})\text{C}^{12}$ the levels in $\text{C}^{12}$ would have to lie at 4.4, 7.4, and 9.5 Mev.
The conclusions of Bonner and Brubaker have been confirmed by recent work due to Gibson, (Gi49) using separated isotopes. They find neutron groups corresponding to levels in $^{11}_C$ at $2.02 \pm 0.10$, and in $^{12}_C$ at $4.47 \pm 0.10$, $9.72 \pm 0.10$, and possibly at $7.7$ Mev. The last mentioned group may be due to $^{10}_B$ contamination in the separated $^{11}_B$. This will be discussed more fully later.

There, is of course, much other evidence for many of the levels mentioned in this discussion. A good summary of the evidence up to 1948 may be found in the review article by Hornyak and Lauritsen. (Ho48)
CHAPTER III

PURPOSE OF THIS EXPERIMENT

Because the evidence on the polonium-beryllium gamma ray spectrum is of a somewhat doubtful nature, mainly due to statistical difficulties, it was believed desirable to make a careful investigation of this spectrum with a pair spectrometer. This was made possible by the loan of a two curie polonium-beryllium source from Los Alamos Scientific Laboratory.

It was believed desirable also to investigate the gamma spectrum from boron isotopes bombarded with deuterons, since this had never been done with separated isotopes and the assignment of the gamma ray lines to the two isotopes was uncertain. This spectrum gives information on some of the same levels in C\textsuperscript{12} involved in the Be\textsuperscript{9}(\alpha,n)C\textsuperscript{12} reaction. The separated B\textsuperscript{10} isotope was obtained from Oak Ridge National Laboratory.
CHAPTER IV

DESCRIPTION OF THE APPARATUS

A pair production spectrometer was constructed for the purpose of this investigation, and for the investigation of other high energy gamma rays. The attainment of sufficient intensity with a pair spectrometer operating in a fairly low energy range was found to be a serious problem. The original model (Te47, Te48) did not have sufficient intensity to be very useful. The final model was designed for high intensity, though it can be used with better resolution and less intensity if strong enough gamma radiation is available.

This spectrometer uses 180° focusing of the pairs produced in a thin radiator by gamma rays from the source. The particles are counted by four Geiger-Muller counters on either side of the radiator (See figure 1). Coincidences between the counters, in all sixteen possible combinations, can be measured as a function of magnetic field and of the distance between counters. The distance between the points at which an electron and a positron will strike the plane of the counters does not depend, to a first approximation, on the way in which the energy of the gamma ray is divided between them. This approximation is quite accurate for high energy gamma rays, as long as both particles are at relativistic velocities. This allows the use of a large radiator and banks of counters, since the gamma ray energy need not be divided equally between the two particles.

This spectrometer has several important features in common with
PAIR PRODUCTION SPECTROMETER FOR GAMMA RAYS
the pair spectrometer used by Walker and McDaniel. (Wa48) These features include the use of a large radiator and banks of counter, the lack of baffles (necessarily, because of the previous features), and the use of a clearing magnetic field to remove secondary particles ejected by gamma rays in passing through the vacuum wall of the spectrometer. However, the Rice Institute spectrometer is designed for higher intensity and somewhat less resolution.

The apparatus consists of the following parts: the evacuated magnet box, the eight counters, lead shielding both inside and outside the vacuum box, the large magnet with its regulator and potentiometer circuits, and the electronic apparatus associated with the counters.

The vacuum box is shown in figure 1, with the counters and most of the lead shielding in place. Some lead shielding was added in most of the work, on the outside of the box, for further protection of the counters from direct gamma radiation. The vacuum box is shown in cross section in a plane perpendicular to the magnetic field. The box is four inches deep in the direction of the field, this being the distance between pole pieces. The outside diameter of the cylindrical part of the box is 27.5 cm, and its height, not considering lead shielding or vacuum connections, is 27.6 cm. The box is made entirely of brass, with soldered joints. The top of the vacuum box is a removable brass cover, with an O-ring seal recessed in a circular groove. The entire interior of the box, except for a part of the region above the radiator, is lined with 1/8" aluminum to reduce scattering effects. Since the brass walls on the pole face sides are 1/16" thick, this reduces
the distance between interior walls to \( \frac{3}{4} \text{"} \). The thin windows between
the vacuum box interior and the counters are of .004" brass shim stock,
soldered to the vacuum box. These windows extend the entire distance
between the walls of the box.

The radiator is mounted in the plane of the thin windows, and
is supported on two sides, the sides adjacent to the poles. Various
radiators were used; the dimensions in general were approximately 8.7
cm square. However, the area effective for pair production is approxi-
mately 8.1 cm by 5.4 cm, the short dimension being parallel to the mag-
netic field. The distance of the source from this radiator was usually
25.5 cm.

The counters are milled out of two Muntz metal blocks, four
counters in each block. The thin window soldered to the counter block,
covering all four counters, is .002" brass shim stock. The counter
wires are 5 mil tungsten, spot welded to \#18 nickel wire; the nickel
wires are soldered between Kovar seals. Thus both ends of the counter
wire are accessible, for the purpose of flashing the wire. Each counter
is 1.14 cm wide and 1.20 cm deep, with 0.05 cm walls between the counters.
The effective length of the counters between the Kovar seals is 9.0 cm
(3\frac{1}{2}""); the overall length is 14.6 cm (5 3/4\"); to accommodate this
length between the pole pieces, channels are recessed 1" deep into the
pole pieces, giving an available distance of 6\". The average distance
of the counters from the center of the radiator is 8.86 cm. The counters
are filled through a Hoke valve, all four counters in a block being
filled simultaneously; the counter volumes are interconnected by means
of small holes near the interior ends, well away from the sensitive volume. The counter filling was usually argon-alcohol, at a pressure of 22 cm of argon and 1 cm of alcohol. This filling was found to give the best operating characteristics.

The pole pieces are circular, and 10.5" in diameter, nearly the same size as the outside diameter of the magnet box. The center of the pole pieces is placed slightly below the center of the cylindrical part of the magnet box. That portion of the field between the top of the spectrometer and the radiator serves as a clearing field to remove at least partially the secondaries produced by gamma rays in passing into the magnet box. (The vacuum wall of the box is made thin at the point of passage—about 1/64"—to reduce the numbers of these secondaries). The magnetic field is found to be sufficiently uniform in the region of the desired electron paths; it is uniform to within 1% for most of the region in question, and drops off by 2% for portions of the outermost paths. The current in the water-cooled magnet coils is furnished by a 400 ampere, 25 kilowatt generator driven by a 40 horsepower induction motor. The resistance of the magnet coils is about 1/10 ohm. The field current for the generator is supplied by a small 125 volt D.C. generator driven by the same motor.

The magnet current is controlled by varying the field current of the generator, both by means of rheostats in series with the generator field winding, and by an electronic regulator which carries part of this current. The regulator is a direct current amplifier, with the output voltage of the generator as its input, and part of the generator field
current as its output. The input stage is a 6SL7 double triode used to amplify the difference between the generator output voltage and a reference voltage furnished by a variable tap on the high resistance (one megohm) in series with a 45 volt dry cell. The amplified difference voltage controls the plate current passing through parallel-connected 6L6 beam power tubes. The plate voltage of these power tubes is the output of the small exciter generator; the plate current (limited to 200 milliamps by fixed bias) is part of the current passing through the generator field.

This method of regulation of the output of the generator was chosen in preference to direct regulation of the magnet current because of the difficulties involved in regulating several hundred amperes flowing through the magnet, as compared to an ampere or less flowing through the generator field.

The magnet current is measured by means of a potentiometer, galvanometer, standard cell, and a 66.7 micro-ohm shunt in series with the magnet current. The potentiometer scale allows the current to be read to approximately 0.15 amperes. The current is maintained constant to 0.2 amperes, more or less, by the regulator and by rheostat regulation of slow drift. Since the currents used were in the range of 25 to 400 amperes, the current was held constant to better than 1% even in the worst case; generally the accuracy was of the order of a few tenths of one percent. This is quite enough for the present experiments, where other sources of error are of equal or greater importance.
The magnetic field was measured with flip coils and a Cambridge fluxmeter. The flip coil dimensions were carefully measured, and the fluxmeter was calibrated against a Cenco line-turn standard. The fluxmeter and the line turn standard were in agreement within 1%. The fluxmeter was found to be slightly non-linear in that it was about 1% less sensitive in the outer portions of its scale than in the center. The field values obtained with the two flip coils differed by 1.5%. Since the dimensions of the larger coil were more accurately known, the readings given by the smaller coil were corrected by this amount.

The measurement of the field by the flip coil and fluxmeter method has an inherent inaccuracy of at least 1% or 2%, if absolute values are to be obtained, though the relative accuracy is somewhat better than 1%. No absolute measurement of the field has been attempted.

The inhomogeneities of the field were measured at several currents, in various areas between the pole faces. As expected, the field is quite homogeneous at the center falling off rather gradually by 1% at a distance of 3 inches from the center, and somewhat more rapidly to 3% less than the maximum value at a ¼ inch distance. Since practically all of the paths from points on the radiator to the counters, leaving the radiator at an angle less than 30° from the perpendicular, lie within ¼ inches of the pole face center, and most lie within 3½ inches, these inhomogeneities were not felt to be very important. These values were measured half way between pole faces, and it was found that the field nearer the iron was, of course, more uniform.
The effect of hysteresis on the field was investigated by measuring the field through various cycles of the magnet current. The field values obtained with decreasing current were found to be about 15 gauss higher than the values obtained with increasing current, in the unsaturated region. This is a small effect, of the order of 1% at the field value needed to measure the pairs from a 4 Mev gamma ray. It was found that the field value obtained was always the same, to within the reproducibility of the measurement (a few tenths of 1%), if the current setting was made by increasing the current from zero to the point desired. Reproducibility was also quite good for decreasing currents, if the decrease was made from a near-saturation value. The field measurements used were made with increasing current, and all pair spectra were measured with increasing current.

The one inch deep slots in the pole faces which receive the ends of the counters were found to have no appreciable effect on the field except within a short distance from the pole face. In any event, field homogeneities at the ends of the electron paths have a much smaller effect than in the midpoints of the paths.

Because of all the various sources of inaccuracy in the absolute determination of the magnetic field as a function of current and of position, it was felt that the most accurate values of gamma ray energies would be obtained by calibrating the pair spectrometer with a high energy gamma ray of accurately known energy. The 2.62 Mev gamma ray from ThC\(^{22}\) was used as a standard for this purpose. It is necessary to correct the measured 14 value at peak pair yield for a shift in the peak
due to the properties of 180° focussing. Since the pair particles leave
the radiator with directions making a small angle about the perpendicu-
lar, peak pair yield is obtained at a value of $H_P$ slightly smaller than
the true value. It is found that the calculated value of the peak
shift agrees with the observed value so well (for the 2.62 Mev line)
that no other correction to the $H_P$ value is necessary. This is certain-
ly accidental, since the field is not known to this absolute accuracy.

The electronic apparatus associated with the counters consists
of the amplification and coincidence circuits (Figure 2) and four scalers.
Two of the scalers (Nuclear Instrument Co.) have built-in 1500 volt
regulated power supplies; these are used to supply the counter voltages,
with one power supply for each block of four counters. It is unneces-
sary to use different voltages for the counters in a single block,
since it is found that the plateau characteristics of the four counters
in each block are identical to within a few volts at approximately
1300 volts.

The pulse output from any counter tube passes through a coaxial
cable into a univibrator stage, which when triggered by the counter
pulse produces an output pulse of about one microsecond length, the
height and shape of the pulse being unaffected by variations in the size
of the input pulse over a reasonable range. These uniform pulses are
fed into cathode-follower type coincidence circuits which have a measured
resolving time of 0.5 microseconds. The coincidence outputs are then
taken into the four scalers through coaxial cables. The Atomic scalers
are somewhat less sensitive than the Nuclear scalers, so that simple
**Figure 2**

Amplification and coincidence circuits

- **Univibrator Stage (one of eight)**
  - 6J6
  - Sens.
  - 1mA
  - 39kΩ
  - 15kΩ
  - 510kΩ
  - Input
  - 2kΩ
  - 4.7kΩ
  - Gains

- **Coincidence Circuit (one of sixteen)**
  - 6SL7
  - 59μF
  - 180μF
  - To other 6SL7 grids
  - 62kΩ (common)
  - 2kΩ
  - 4.7kΩ
  - 62kΩ (common)

- From another univibrator

- From coincidence circuits

Output
two stage amplifiers are needed to give a large enough pulse size for reliable operation. No amplification is needed for Nuclear scaler inputs.

Coincidences can be measured between all possible pairs of counters, one of which is on the positron side and the other on the electron side. Since there are four on each side, sixteen coincidence circuits are necessary. There are, however, only seven different values of counter separation, with each value giving a different $H\rho$ for the same magnetic field. The coincidences between pairs of counters corresponding to a single value of counter separation (counter separation equals $\rho$, where $\rho$ is the path radius for an electron or positron with half the gamma ray energy) are brought to the same output fitting and go to the same scaler. The numbers of counter pairs corresponding to the seven values of counter separation are, in order of increasing separation, 1, 2, 3, 4, 3, 2, 1, a total of 16. The counters are numbered from 1 to 4 in order of increasing distance from the radiator, those on the electron side being numbered 1A to 4A, and those on the positron side being numbered 1B to 4B. Thus, the minimum counter separation occurs for the combination 1A-1B, the next separation corresponds to 1A-2B and 2A-1B, the next to 1A-3B, 2A-2B, and 3A-1B; and so on. For mnemonic reasons the corresponding coincidence output channels are numbered from 2 to 8, the number of the channel being equal to the sum of the numbers of any pair of counters feeding into it. Channel 5 is the central channel, with the maximum number of
coincidence circuits (four) feeding into it. For economic reasons, four instead of seven scalers were used, in channels 3, 4, 5, and 6. This means a loss of $4/16$ of the information available with seven scalers, but somewhat less complexity in collecting data. The weighting factors of the channels used are then 2, 3, 4, and 3 for channels 3 to 6, a total of $12/16$ of the possible coincidence output.

Some difficulty was experienced in putting the output of as many as four cathode-follower type coincidence circuits into a single scaler. The coincidence circuits tended to interact in various undesirable ways. Eliminating the interaction by putting resistances in series each coincidence output is undesirable, because the size of the coincidence output pulses is cut down by essentially the same amount that the interaction is cut. This difficulty is eliminated by using crystal diodes in series with each output, so a low resistance is presented to pulses traveling from a coincidence circuit into the scaler, but a high resistance is presented to a pulse traveling from one coincidence circuit cathode to another coincidence cathode. This device has worked very satisfactorily.

It is desirable to count pulses from single counters as well as coincidence pulses, both for the purpose of testing and intercomparing the amplifier and coincidence circuits and for the purpose of calculating the correction necessary to coincidence rates for accidental coincidences (The accidental coincidence rate between two counters is given by $A = 2n_1 n_2 t$, where $A$ is the number of accidental counts per unit time, $n_1$ and $n_2$ are the counting rates of the two individual counters,
and is the resolving time of the coincidence circuit, in the same time units). For this purpose switches are placed in series with each of the 32 plate connections of the 16 coincidence circuits, so that each circuit may be made into a simple cathode follower amplifier for either of its two inputs. It is necessary to use only eight switches for this purpose, each switch controlling four triodes (the four triodes in coincidence with a single counter). This allows counting rates to be measured simultaneously for the four counters in either block, so that little time is spent measuring these single counting rates in actual practice. It is also possible to measure the counting rate of any one counter simultaneously through all the output circuits to which it is connected, so that any loss of counts or addition of counts due to circuit difficulties in any channel may be instantly detected. This check was made periodically through the work to be described, for both halves of every coincidence circuit in use. The output pulse when a cathode follower coincidence circuit is used as an amplifier is very closely the same in shape and size as the coincidence pulse. The only detectable difference is that the coincidence pulse is very slightly larger. This is convenient, since it allows the gains and pulse discrimination levels of the scalers to be set easily by means of single (not coincidence) pulses, which are readily available at good counting rates. This procedure has been checked against the more inconvenient procedure of checking these gain settings with coincidence pulses, and has found to be equivalent. If no single counts are lost because of low gain setting, no coincidence counts will be lost, since these are slightly larger. The importance of accurate
setting of the scaler gain is that if gain is too low, coincidence pulses are lost, and if gain is too high, the resolving time is lowered. It has been found that the resolving time is relatively insensitive to variations in scaler sensitivity, if this sensitivity is set slightly higher than is necessary to count single counts. Small variations in scaler sensitivity or coincidence output pulse size will thus have no appreciable effect on the counting rates.

The accidental rates obtained with 0.5 microsecond resolving time were in general only a small percentage of the true counting rate, and in some cases negligible. There is thus found to be no necessity to use a smaller resolving time, with the resulting difficulties with counter time lag and circuit complication.

The 110 volt AC supply to the coincidence circuits and amplifiers was held constant by a Kleeket voltage regulator at all times. During all the work done in connection with the Van de Graaff generator, all electronic circuits had regulated AC supply.

A small oscilloscope was used to monitor the counter pulse sizes at the input to the coincidence chassis. This was done at the beginning of an experimental run and at occasional intervals throughout a run. This was the means by which the counter operating voltage was set and maintained constant during a run. (The counter voltages and pulse sizes remained quite steady in general.) It also served to detect any malfunction of the counters which would result in a change of the appearance of the pulses (such as multiple pulses or excessive hum). The oscilloscope was not connected to the counter circuits when
data was being taken, of course.

This oscilloscope was designed for measuring pulse size and has an attenuation control which covers a range of 60 decibels in units of two decibels. The same oscilloscope was used in checking the output of the coincidence circuits, in order to set the sensitivity controls of the univibrator input stages in the center of the range of proper operation. Outside of this range (which depended on the input pulse size) the appearance of the output pulses changed and, if far enough outside, the counting rates changed. The oscilloscope was one of the most sensitive means of detecting improper operation.

In general, the electronic circuits gave little trouble and all these checks were merely precautionary and reassuring. Their purpose, of course, was to ensure that any trouble which did develop would be detected before much questionable data had been taken.
CHAPTER V

EXPERIMENTAL PROCEDURE

In the operation of the spectrometer, data was obtained for four different values of $H \rho$ simultaneously, separated by approximately 7.0% between each two values. In taking a rapid survey of a pair spectrum, field settings were chosen so that the highest $H \rho$ value for each setting of $H$ was the same as the lowest $H \rho$ value for the next higher setting of $H$. This overlap gave the data points slightly more equal weight, since the outermost values of $H \rho$ have least weight, (fewest counter pairs). In this way, the change in $H$ between any two successive settings is about 20%, and the entire spectrum is covered by a few settings of the magnetic field. For the precise measurement of a spectrum, the field values were changed in steps of 3.5%, so that data was obtained for values of $H \rho$ with a uniform separation of 3.5%, with four measurements of the pair yield corresponding to each value of $H \rho$. (One measurement from each of the four channels in use). The points could have been spaced more closely, if desired, but this was not felt to be necessary. The value of this overlapping is twofold; it provides a good check on the consistency of the data and on the proper operation of each channel, and it serves to eliminate the effect of slightly inaccurate channel weighting, since each point is represented by data from the same four channels, in the same proportions.

Inaccuracies in channel weighting come about because of the varying distances of the counters from the radiator. Thus, the average radii
of particle motion for channels 3, 4, 5, 6 ( \( \rho \) is the distance between the centers of the two counters) are 3.83, 4.13, 4.43, and 4.73 cm.

Because the counters are of constant width, at varying distances from the radiator, the proportion of pairs accepted by each pair of counters will vary as \( \gamma \rho \). (This will be discussed more fully in a following section). There is also an effect due to the counter length which tends to cut down the yield of the counters with increasing distance from the radiator. The effect is this: the particles which leave the radiator in the direction perpendicular to the surface stay in a plane perpendicular to the magnetic field, and will surely be counted if the magnetic field is set correctly. The particles leaving the radiator with a small component of velocity toward the pole pieces will still hit within the length of the counter, if the point on the radiator is not too close to the pole face and the velocity component is small enough. However, for any given radiator point, there is a definite solid angle within which the initial direction of the particle must lie in order for it to hit a given counter (as always, for the proper field setting)--and this solid angle is smaller, the farther away the counter. There is thus an effect due to the counter length which also tends to decrease the yield of the counters with increasing distance from the radiator. We note also that the resolution will be somewhat better for the outermost pairs of counters, because the ratio of counter width to path radius is smaller. The resolution would then decrease in numerical value as \( \gamma \rho \), if there were no other causes of loss of resolution than the counter width. This is not the case, of
course, so that the resolution does not change so much between channels. It is observed, however, to be slightly better in channel 6 than in channel 3.

The effect, then, of the distance between a pair of counters on the yield obtained for a given value of $\rho$ is to cause the yield to vary with $\rho$ somewhere between $1/\rho$ and $1/\rho^2$. This variation with $\rho$ will depend to some extent also on energy, as the effects of angular distribution become less important as the gamma ray energy increases.

The experimental results obtained showed that a correction factor of $1/\rho^2$ was not far wrong. This correction factor, chosen thus somewhat empirically, has been applied to all the data taken. It should be noted that, this correction factor can have no effect on the shape of the curve if the overlapping process mentioned above is used. The actual channel weights used are:

<table>
<thead>
<tr>
<th>Channel Number</th>
<th>Number of Coincidence Circuits</th>
<th>$1/\rho^2$ Factor</th>
<th>Channel Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>2</td>
<td>1.34</td>
<td>2.68</td>
</tr>
<tr>
<td>4</td>
<td>3</td>
<td>1.15</td>
<td>3.45</td>
</tr>
<tr>
<td>5</td>
<td>4</td>
<td>1.00</td>
<td>4.00</td>
</tr>
<tr>
<td>6</td>
<td>3</td>
<td>0.88</td>
<td>2.64</td>
</tr>
</tbody>
</table>

The process of handling data when several channels are overlapped for a given $\rho$ is this: The counting rates in the several channels are added, and then divided by the sum of the channel weights for the channels used. This reduces the data to approximately the counting rate for one pair of counters, spaced the average distance apart (e.g. one pair of counters in channel 5). The effect of slight
inaccuracies in the channel weighting factors, if all four channels are not overlapped, may be to cause slight inaccuracies in the shape of the curve because of the variation in the combination of channels used from point to point of the curve. It is obvious that these effects are entirely eliminated by overlapping all four channels for each point. In this case the only effect of the special values assumed for the channel weights is to divide the sum of counting rates for the four channels by 12.77, the sum of the channel weights, rather than by 12, the actual number of coincidence circuits in use. This affects only the ordinate scale, not the shape of the curve. This desirable procedure of overlapping has been followed in all the important regions of the pair spectra investigated. (At the ends of the region measured in a spectrum there will be a few points which do not represent the overlap of all four channels.)

The other corrections applied to the actual counting rates, in addition to the weighting factors described, are these: a small correction is made for accidentals, using the measured resolving time of 0.5 microseconds. From this corrected value is subtracted the counting rate obtained with no radiator in place, also corrected for accidentals. (The two accidental corrections do not cancel out, because the single counting rates and hence the accidental rates, are lower in the absence of the radiator.) This no-radiator background arises from several causes. One obvious cause is accidental coincidences, for which a correction is made. The other part of this background represents true coincidences from various causes. The effects of cosmic ray showers were made entirely negligible by the fact that the counters lie in a horizontal plane,
with at least four inches of lead over them at all points. The form of the background as a function of \( H_P \) depends on the source of gamma rays, but in general it is a maximum at some relatively low value of \( H_P \), considerably lower than the \( H_P \) for the pair particles, and falls slowly to a negligible value with increasing \( H_P \). It is thought to be caused in part by pairs formed in other parts of the magnet box than the radiator, and in part by coincidences between Compton electrons and the scattered gamma rays. There are other possibilities for the cause of this no-radiator background, such as gamma-gamma coincidences or neutron-gamma coincidences. No successful way was found to reduce this background very much, though numerous methods were tried, on various theories. That simple subtraction of this background is correct (i.e. that the presence of the radiator does not change this effect) is indicated by the satisfactory way in which the pair yield curves are brought down to zero at the low energy end. The presence of this background at low pair energies decreases the effective sensitivity of the pair spectrometer in this region, because of the statistical errors inherent in the process of observing a quantity which is smaller than the background.
CHAPTER VI

RESOLUTION AND YIELD OF THE SPECTROMETER

There are several factors which affect the resolution; the most important of these are the loss of energy of the electrons and positrons in passing through the radiator, the angular distribution of pair particles leaving the radiator, scattering in the thin windows between the interior of the vacuum box and the interior of the counters, and the width of the counters.

The loss of energy of the particles due to passage through the radiator is not an important effect in the work to be described. For most of the work a radiator of 31.0 mg/cm² tin was used, with a thickness of 42 kilovolts for fast electrons. Since the pair particles, on the average, pass through half the radiator thickness, the average loss of energy is 21 kilovolts per particle, or a total of 42 kilovolts for the pair. This corresponds to a 1.0% average loss, in terms of momentum, for the pairs produced by a 4.5 Mev gamma ray, or 0.5% for a 9 Mev gamma ray. The radiator used in the most careful measurement of the 2.62 Mev gamma ray of ThC²⁺ was 20.7 mg/cm² thick (28 kilovolts for a fast electron) giving an average loss of 1.3% in HP. These effects are not very important compared to the effect of counter width. The effect of scattering in the thin foils between the magnet box and counters is minimized by making the distance between the foils as small as possible. Since a heavy foil sags under the effect of air pressure less than light foil, a compromise is necessary between the
scattering in the foil and the sag. For the foils actually used (.004" brass shim stock on the magnet box and .002" brass on the counter block) the maximum distances of sag are found to be about 3/32" for the vacuum box and 1/32" for the counter foil, so that the maximum distance between the two foils at any point is 1/8" (this was measured with the counters in place and found to be correct). The sag of the counter foil has essentially no effect, since a fast particle scattered in the counter foil will still cause a count in the counter directly behind the point of scattering; thus, for this foil, only the thickness is of importance, as a scattered electron may pass through a counter wall and count in more than one counter. The distance between the magnet box foil and the walls between counters is the important parameter; it is a maximum of 3/32" and an average of about 1/16". For a pair electron of average energy produced by a 4.5 Mev gamma ray, the multiple scattering theory of Rossi and Greisen (Ro41) gives a root mean square scattering angle of 45° in this foil. This is probably larger than the actual scattering angle, as the formula is applicable only to quite small angles, and experiment (Ol40) seems to verify the conclusion that the theory in question gives results for thick foil multiple scattering which are too large. This scattering (in the magnet box foil) will cause a given counter to miss some particles which it should have counted, and count a few which should have gone into the adjacent counter. This should have no important effect on the resolution of the counter, but should give a slight tail on each side of a pair yield peak, due to particles which have passed through more than one counter.
The counters are 1.14 cm wide, with .05 cm walls between them. Since fast electrons striking the wall between two counters will almost certainly be scattered into one of them, we may take the effective width of the counters to be 1.19 cm. If there were no scattering in the magnet box exit foil, the counting efficiency of a single counter as a function of the point of impact on the foil would be represented by a nearly rectangular curve with the width at half height given by \( w \), the counter width (1.19 cm). The effect of scattering in the exit foil is to make the efficiency curve more rounded and less rectangular, but the increase in width at half height is probably negligible. Since the average distance of the counters from the radiator center is 8.86 cm, the resolution for particles leaving the center of the radiator is 13.4%. However, the nature of the pair production process, as a result of which either particle may have any fraction of the total kinetic energy, reduces the resolution for pairs to half this figure. It can be seen that, in the idealized case of no scattering, the counting rate for pairs as a function of \( M \) will be a triangular curve of width at half height 6.7% and a base 13.4% wide, in terms of the momentum corresponding to the peak of the triangle. The effect of exit window scattering will be to round the corners somewhat and add tails on both the high and low momentum sides, but to affect the half width only slightly.

The effects on the resolution of the spectrometer of slight inhomogeneities in the magnetic field, and of fluctuations in the magnet current, are small, as has been pointed out in an earlier sec-
tion. The magnitude of the effect of inhomogeneity on the resolution is probably less than 1%, and the effect of current fluctuations is much less than 1%, because of the current regulator.

The effect on the resolution (and on the yield) of the angular distribution of pair particles leaving the radiator is important, particularly at low energies. With 180° focussing, an electron leaving the radiator in a direction which is not perpendicular to the surface will necessarily strike the counter area at a distance from the radiator less than the maximum distance, which is attained only by those electrons leaving at 90°. This effect of course lowers the average value of $H\rho$, as measured by the spectrometer.

There are three basic factors controlling the angular distributions of the pair particles on leaving the radiator; these are the angle at which the gamma rays strike the radiator, the angular distribution of the particles ejected in the process of pair formation, and multiple scattering of the pair particles in the radiator. We can best consider these effects by finding in what way the point at which an electron (or positron) strikes the counter area depends on the direction in which it originally left the radiator.

We consider the motion of an electron in a uniform magnetic field $\mathbf{H}$, taking the origin of coordinates at the point of origin of the particle in the radiator. We take the $z$-axis in the direction perpendicular to the radiator; $x$- and $y$-axes lie in the plane of the radiator, the $y$-axis being the direction of the magnetic field. We define three useful angles: $\theta$ is the angle between the direction $OP$ of initial motion of
the electron, \( \phi \) is the azimuthal angle, the angle between the positive x-axis and the projection of OP on the xy plane, and \( \alpha \) is the angle between the positive z-axis and the projection of OP on the xz plane. A consideration of the path of an electron of charge e moving with relativistic momentum \( p \) in a uniform field \( H \) produces the following equations (La40) for the location of the point \((x, y)\) at which the electron strikes the plane \( z = 0 \):

\[
x = \frac{2p}{He} \cos \theta \\
y = \frac{p}{He} (\theta - 2x) \sin \theta \sin \phi
\]

It is to be noticed that the distance which the electron travels along the x-axis—that is, the difference between its initial and final values of \( x \)—is independent of the azimuthal angle \( \phi \).

The fractional amount by which \( x \) is less than its maximum value \( \frac{2p}{He} \) is given by \( \theta^2/2 \) for small angles.

If we consider the effect of the angle at which the gamma ray strikes the radiator, we find that the fractional decrease in \( x \) due to this cause is given by \( \theta^2/4c \), when averaged over a rectangular radiator. Here \( \theta^2/c \) is the maximum angle which the direction of the gamma ray makes with the z-axis, corresponding to a point in a corner of the radiator. Using the effective area of the radiator, \( 8.1 \times 54 \text{ cm}^2 \),
and the distance from source to radiator (25.4 cm) we find that the average error in $\Phi$ due to this cause is 0.61%. The assumption made in this analysis is of course, that the particles are emitted in directions differing very little from the direction of the gamma ray.

The complicated nature of the angular distribution due to the pair formation process has been discussed in a previous section. The distribution has a characteristic angle (within which half the particles fall) given, for fairly high energies, by $\frac{m}{E}$ where $m$ is the electron rest mass energy and $E$ is the total energy of the electron, including the rest mass. This angle is equal to 22.4° for pairs formed by the ThCγ gamma ray of 2.62 Mev, and is 6.5° for a gamma ray of 9 Mev. These angles apply to electrons and positrons having half the total energy of the gamma ray.

The electrons and positrons undergo multiple scattering before leaving the radiator, unless they are produced at the forward edge. The angular distribution due to this process has been calculated by Rossi and Greisen (Ro41) on the assumption of high energies and small angles. The root mean square angle of multiple scattering is given by $\theta_0 = \frac{E_s}{p \beta^2} t\frac{\gamma}{\alpha}$, in which formula $E_s = 21$ Mev, $p$ is the electron momentum in Mev, $\beta$ is the electron velocity in units of the velocity of light, and $t$ is the thickness of the scatterer in radiation lengths (the radiation length of tin, the type of radiator used in most of this work, is 8.72 g/cm²). The fraction of particles scattered into unit solid angle at an angle $\theta$ from the original direction is a Gaussian function of $\theta$, given by
\[ G(\theta) = \frac{1}{\pi \theta_0^2} e^{-\left(\frac{\theta}{\theta_0}\right)^2} \]

In the work to be described the radiators used were always of sufficient thickness that the multiple scattering effect was larger than the angular distribution of pair formation. It should be noted that the energy dependence of the two types of angular distribution is nearly the same, inversely as the total energy or momentum. For a radiator of 31 mg/cm² tin, used in much of this work, the ratio of the characteristic angles of multiple scattering and pair production is:

\[ \left( \frac{E_s}{\theta_0} t^{1/2} \right) / \left( \lambda / \varepsilon \right) \approx 1.8 \]

In this case the characteristic angle of multiple scattering has been calculated for half the thickness of the radiator, since this will give the root mean square value of the angle for particles formed throughout the radiator.

To approximate the angular distribution caused by the combination of pair formation and multiple scattering that we are concerned with, a method which is probably not greatly in error, or at least not much more so than the application of the above formulas at relatively low energies and large angles, is to consider that the resultant distribution is of Gaussian form, with a root mean square angle given by the square root of the sum of the squares of the two characteristic angles. This amounts to considering that the pair production distribution is approximately Gaussian. This approximation is certainly in error by an appreciable amount. However, no adequate theory has yet been developed.
for either of the contributing angular distributions (pair production
and multiple scattering) at the fairly large mean angles with which
we must deal in the region of a few million electron volts.

We shall consider the distribution in the plane \( z = 0 \) (the plane
of the radiator and counter windows) of the points at which electrons
strike if they leave the radiator with an angular distribution given
by \( n(\theta, \phi) \), the number of electrons per unit solid angle per second.
To simplify the treatment, we do not concern ourselves with the
distribution of the impact points as a function of \( y \). It is then a
simple matter to show that the number of electrons arriving per second
between \( x \) and \( x + dx \) is, for \( x < 2p/h_e \),

\[
I(x) = \frac{n(\theta)}{p} = \frac{n(\cos^{-1} \frac{H_e x}{2p})}{p}
\]

in which \( n(\theta) \) is now the average of \( n(\theta, \phi) \) over the entire range
of the azimuthal angle \( \phi \). The distributions we have been considering
do not depend on \( \phi \) in any case, if we consider only the case of normal
incidence of the gamma rays on the radiator, as at the center of the
radiator.

The effect of the finite length of the counters has been
mentioned previously; there is a solid angle within which the initial
electron directions must lie in order that the impact points do not
lie outside the length of the counters. For angular distributions of
small characteristic angle almost all the electrons strike within the
counter length, so that \( I(x) \) gives very closely the number of electrons
which will be counted per unit distance. For large-angle distributions
it is necessary to allow for the number of particles not counted because
of the effect of counter length. This may be done by means of the
relations between \( x, y \), and the angles \( \Theta, \phi, \) and \( \alpha \), and has been
done for several points of the radiator, for use in estimating counting
losses due to this effect. At high gamma ray energies this loss is
small; it is large at low energies but cannot be accurately calculated
because of the only partially known nature of the angular distribution.

In order to calculate accurately the dependence of the pair
counting rate on \( H \phi \) for a gamma ray of a given energy, it is necessary
to consider a definite point on the radiator, find the dependence of
the counting rate of a single counter on the magnetic field and on the
electron momentum, taking into account the effects of angular distribution,
including the loss due to counter length, and to integrate the product
of two such single counter transmission functions over all the values
of momentum which the electron may have. This is a process of folding
together two transmission curves, one as a function of the electron mo-
mentum and the other a function of the corresponding positron momentum,
the sum of the energies being constant. This calculation must allow
for the numbers of electrons lying in each energy range, but the fact
that this is nearly a constant for a gamma ray of several million
volts simplifies this matter. It would then be necessary to perform
this complete operation for a range of radiator areas, since the counting
losses depend both on the location of the radiator point and on the
momentum of each of the particles. It would be considerably more accurate
to perform this operation for points at various depths within the
radiator, as this affects the angular distribution most importantly.
Finally, the integral of these results over the volume of the radiator would give the pair counting rate as a function of $4\rho$.

Obviously such an elaborate calculation is not justified for angular distributions which are known only roughly. However, we can obtain information of interest from certain simplifying assumptions. We may consider only the center of the radiator, assume a Gaussian angular distribution, neglect the effect of counter length, and carry out the operation of operation of folding together the two transmission curves found under the above assumptions. We may consider the case of two counters, at equal distances from the radiator point, with the width of the counters equal to 6.7\% of the distance between them, as is the average case for this spectrometer. This operation has been performed for three such simplified cases, with the root mean square angles equal to 0°, 13°, and 27°. These angles were chosen to represent, respectively, the effects of a negligible angular distribution (very high energy) and the effects of a 31 mg/cm² tin radiator at 9.1 and 4.5 Mev, assuming the theoretical angular distributions to be approximately correct. The results are plotted in figure 3 as a function of $\lambda = H e \theta / \rho$.

The quantity $\rho$ is half the distance from the center of either counter to the center of the radiator, while $p$ is the momentum which each particle has in the case of equal division of gamma ray energy. The ordinate is the fraction of the total of pairs formed which are counted by these two counters in coincidence, on the assumption that all distributions of energy between the two pair components are equally probable. The curves are quite general in nature, the only parameters entering
THEORETICAL PAIR TRANSITION FOR SEVERAL ANGULAR DISTRIBUTIONS (Φ: RMS ANGLE DUE TO MIA PRODUCTION AND ANGULAR CORRELATION)

ASSUMED OR DETERMINED THICKNESS:
31 mg/cm²

ASSUMED CURVATURE RESOLUTION: 6 ft.

Fraction of Total Pairs Counted

\[ \lambda = \frac{He}{p} \]

Figure (3)
into the calculation being the root mean square angle and the resolution width due to the counters (6.7%).

The transmission curve for pairs leaving the center of the radiator in a direction perpendicular to the radiator is seen to be triangular, with half width 6.7% and a maximum value of 6.7% transmission for $H_{\gamma} = p$, or $\lambda = 1$. This is of course a limiting case, which is approached more closely as the gamma ray energy increases. In this idealized case, the peak is entirely unshifted, the half width is just that due to the counter width, and the maximum yield of pairs is obtained --- 6.7% of the total number produced, for a single pair of counters. Four pairs of counters, as in channel 5, would count 26.8% of the pairs formed in the radiator in this idealized case. This of course considers no effects, other than the angular distribution, which might reduce the yield or increase the width of the curve. It should be noted that the transmission curve is not an isosceles triangle, but that the endpoints lie 7.2% above and 6.2% below the value of $H_{\gamma}$ corresponding to the peak.

The transmission curve for $\theta = 3^\circ$ is similar in general shape to the ideal curve, except that the corners have been rounded. The maximum yield is 5.4%, the peak is shifted down by 2.0% from the correct value, and the width at half height is increased from 6.7% to 7.9%. If we assume that the new width squared is equal to the sum of the squares of the counter resolution and a width due only to angular distribution, we obtain 4.2% as the resolution width due to angular effects. This transmission curve is probably not a bad approximation to the actual angular effects at 9.1 Mev, though of course all other
effects have been neglected. Considering these other effects, such as the loss due to finite counter length and the deviation from perpendicular of the gamma ray direction, we may make a rough estimate that about 3% of the pairs formed will be counted at this energy, for the assumed angular distribution from a 31 mg/cm$^2$ tin radiator.

Taking into account the pair cross section at 9.1 Mev in 31 mg/cm$^2$ tin and the solid angle subtended by the effective area of the radiator at the source (.067 steradians, or 0.54%) we can calculate that this spectrometer will count one electron-positron pair for 8x10$^6$ gamma ray quanta emitted by the source, for each pair of Geiger counters. It is probable that this estimate is not in error by as much as a factor of two.

The transmission curve for $\theta_0 = 27^\circ$ is considerably more flattened. The maximum yield is 2.4%, the width at half height is 12.8%, in terms of the $\text{H-P}$ for maximum yield (the half height width for the smaller angle was calculated on the same basis), and the peak is broadened and shifted to a value of $\text{H-P}$ which is 6.0% lower than the correct value. The resolution width due to angular effects may be calculated, in the same manner as described above, as 10.9%. This transmission curve cannot be an accurate representation of angular effects at 4.5 Mev, as too many factors have been neglected which are quite important here. The effect of counter length on a 27$^\circ$ angular distribution will be considerable, since many of the electrons emitted from the central area of the radiator will strike the spectrometer walls if their angle from the perpendicular much exceeds 18$^\circ$, in a magnetic field calculated to
focus them at the counter distance. Furthermore, at these large mean angles the angular distributions are not known with any degree of accuracy. The loss due to counter length has two effects; it reduces the yield of pairs counted, and it eliminates most of the pairs leaving the radiator at large angles. This will reduce the broadening of the transmission curve, and in fact will put an upper limit on the extent to which the angular distribution can broaden the curve.

It is obvious that the effect of angular distribution on the width and peak shift of the transmission curve cannot be calculated with any degree of accuracy at these low energies. However, we may conclude that there is probably a general relation between these two factors, the width and the peak shift. In both of these calculated cases the peak shift was closely equal to half of the added width due to angular distribution, the added width being calculated by the difference of squares. It is not an unreasonable assumption that this relation will hold with fair accuracy over the range of halfwidths we have considered.

This relation holds true in many cases in which there are combined the effects of a transmission curve of a general triangular or Gaussian form and a shifting effect with width of the same general magnitude as that of the transmission curve, or smaller. An obvious example is the case in which a magnetic analysis is made of the energy of a beam of charged particles which have been produced in a thin foil at all points throughout the foil. If the maximum fraction of energy which may be lost in the foil is given by \( v_1 \), and the resolution of the analyzer is \( v_2 \) (half width of an approximately Gaussian transmission function), then the width of the analyzed spectrum will be approximate-
ly equal to $(w_1^2 - w_2^2)^{1/2}$ and the peak will be shifted by approximately $w_1/2$ from its true position.

This approach to the problem of estimating the peak shift seems to be nearly the only practical one in the present case, in which the actual shift cannot be accurately calculated because of the form of the angular distribution at low energies is not known with any accuracy.

Similar arguments apply to the widths and peak shifts caused by other factors which are of smaller importance than the angular distribution, such as the energy loss in the radiator and the very slight dependence of the sum of positron and electron momenta on the way in which the energy is divided between them (the total momentum is slightly lower in the case of unequal division, but the effect is of the order of a few tenths of 1% for all the work reported on in this thesis). Thus the process of finding the amount of width in a spectral line which is not due to the 6.7% resolution of the counters will correct for these other factors as well as for the angular distribution effects, and will probably give as accurate a value of the true energy of the pair particles as can be obtained from the data.

This type of correction is not valid for a line shape which is markedly asymmetrical, and should not be applied to such lines. In the case of a radiator which is thick enough to produce multiple scattering effects of considerably greater importance than the angular distribution effects due to the pair production process, those particles which travel through the entire thickness of the radiator will be largely lost due to scattering. This is particularly so because only one of the two pair
particles need be lost to eliminate a coincidence. Thus the forward edge of the radiator will produce the majority of the pairs counted and will have the most effect on the location of the peak. The critical thickness of radiator will be that which produces an angular distribution of the same order as that due to the pair process, or, if the pair angle is very small, of the general order of 18°, beyond which a large fraction of the particles will not be counted. For a radiator of thickness much greater than this critical thickness, the rear edge will be largely ineffective in increasing the peak yield; its effect will be to broaden the observed line shape on the low energy side, without shifting the peak in a proportionate way. This will, of course, give an asymmetrical line, to which we cannot apply the correction discussed above.

For those pair spectra obtained in a relatively thin radiator the peak shift correction discussed above has been applied. Though error may arise because of the approximations made, no other method of correction has been found which will give more accurate results. Various methods of estimating the correct gamma ray energy did not give results differing more than about 1% from the results obtained with the method outlined here.

It does not appear to be possible to form an accurate estimate of the efficiency of the spectrometer at energies much lower than 10 Mev, as the above discussion has shown. The efficiency is obviously considerably lower for low energy gamma rays, even disregarding the lower pair production cross sections. Thus the absolute intensities of low energy gamma rays can only be found by comparison with other gamma rays of similar energy and known intensity.
A: Mesothorium Source: As a check on the operation of the spectrometer, pairs were observed from the 2.62 Mev gamma ray of ThC²⁷. The source was a salt of MsThI, contained in a sealed glass tube. The strength of its gamma radiation was measured by the National Bureau of Standards with a lead-shielded ionization chamber two years previous to this observation and was found to be equivalent at that time to that of 9.29 milligrams of radium in radioactive equilibrium. A similar comparison was performed at Rice Institute at the time of these experiments, using a small Geiger counter in a ¹/₄" thick lead sheath. The counting rate of the thorium source was found to equivalent to that of 10.6 milligrams of radium, though with lower precision than the Bureau of Standards measurement.

The pair counting rate obtained in the most carefully cone of several runs using a 20.7 mg/cm² tin radiator is plotted as a function of $H_P$ (value for one particle) in figure 4. Standard statistical errors are indicated for all of the points. The counting rates given apply equally well to any of the four channels used, when multiplied by the channel weight (channels 3, 4, 5, and 6 have weights 2.68, 3.45, 4.00, and 2.64 respectively). The data has been corrected for accidental counts (about 4% of the peak counting rate) and for a small no-radiator background which was measured as a function of $H_P$. This background dropped slowly to zero with increasing $H_P$, apparently extending to about 7000 gauss-cm; its value in the region of the main peak was
PAIR SPECTRUM FROM ThC⁶⁰, USING 20.7 mg/cm²

TIN RADIATOR
about 4% of the peak counting rate.

The pair yield curve shows a single peak, with a long low tail at high energy. The long tail is probably due in part to pairs, one member of which has been scattered from an interior wall of the spectrometer; another probable source of background is coincidences between Compton electrons produced in the radiator and the scattered quanta (there is about \( \frac{1}{2} \) inch of brass between the radiator and the nearest counter; this would not stop the scattered gamma radiation). The peak is located at \( H_{\varphi} = 3800 \) gauss-cm, and has a height of 34.4 above background. The width at half height is 13.8% of 3800 gauss-cm, and the high energy edge is noticeably steeper than the low energy edge. Taking the square root of the difference between the squares of 13.8% and 6.7%, we find a width of 12.0% due to angular distribution effects and to energy loss in the radiator (about 26 kev thick for a fast electron). Applying the calculated peak shift of 6.0%, we obtain 2.62 Mev as the energy of the gamma ray from ThC\(^{228}\). The fact that this is known to be accurately the true energy from other work (La47, Wo50) indicates that no correction is necessary to the measured value of the magnetic field, if the empirical correction applied above is not in error. However, the order of magnitude of the error involved in this energy measurement is probably not less than 2%, considering the various sources of error. Thus we may write the energy of the ThC\(^{228}\) gamma ray as 2.62 ± 0.06 Mev, as determined in this pair spectrometer. This serves more as a calibration for the spectrometer than as an absolute measurement of the gamma ray energy.
Several observers (see discussion in Fe49) have reported observing a weak gamma ray at about 3.2 Mev from this source. The small fluctuation which may observed in the pair yield at about 3.0 Mev has a height about 2% of the main peak, and is of the same size as statistical fluctuations in this region. We may conclude that there is no gamma radiation in this region of intensity greater than the statistical fluctuations of 2%. Allowing for the increased pair production cross section at 3.2 Mev and for improved operation of the spectrometer with better angular distribution, we may be sure that the present data shows that there is no gamma ray in this region of intensity as great as 1% of the intensity of the 2.62 Mev gamma ray. This is consistent with the data of Bell and Elliott, (Be48) which indicated that any 3.2 Mev gamma ray would have to be of intensity < .2% of the 2.62 Mev intensity.

A ThC source of 9 millicurie strength should emit about $3.4 \times 10^8$ gamma rays per second; comparing this with the observed counting rate of .034 pairs per second per pair of counters (.138 counts per second in channel 4) we find that the efficiency of the spectrometer at this energy is of the order of one pair count for each $1.0 \times 10^{10}$ gamma rays emitted by the source. This is about 1000 times smaller than the effect calculated at 9.1 Mev; the spectrometer is very insensitive at energies as low as 2.62 Mev.

The ThC gamma ray was also observed using a tin radiator twice as thick ($41.4 \text{ mg/cm}^2$, or 56 kilovolts) as in the work just described. The maximum yield was observed to be 45.6 pairs per 1000 seconds per
unit channel weight above background, or about 33% higher than with a radiator twice as thin. The high energy tail was just twice as high as for the thinner radiator. The small increase in pair yield is probably due to the poorer angular distribution from the rear side of the thicker radiator, causing the added thickness to be relatively ineffective in producing pair counts. The half width of the yield from the thicker radiator was about 14.9%, 1.1% wider than the yield from the thin radiator. The width due to angular distribution and energy loss is calculated to be 13.3% by taking the difference of squares. This should produce a peak shift of 6.6%, or 0.6% more than for the thin radiator, if we assume that the shift correction is accurate at this thickness. Because of the statistical errors in this determination, not done as carefully as for the thin radiator, such a shift would not be detectable; the peak appeared to be in the same location.

For purposes of comparison with other data, we may estimate the efficiency of the spectrometer for a 31 mg/cm$^2$ tin radiator at this energy (2.62 Mev). The yield would probably be nearer that of the 41.4 mg/cm$^2$ radiator than that of the 20.7 mg/cm$^2$ radiator. Since the two yields differ only by 33%, we estimate fairly well that the spectrometer counts one pair for each 8x10$^9$ quanta produced at this energy, using a 31 mg/cm$^2$ tin radiator.

B: Polonium - Beryllium Source. After this preliminary work with ThC$^8$, the pair spectrometer was used to observe the gamma rays from a strong polonium-beryllium source loaned by Los Alamos Scientific Laboratory. This was a 0.50 inch diameter beryllium sphere mounted in-
side of two beryllium hemispheres of 0.50 inch inside diameter and 0.78
inch outside diameter. The polonium was deposited between the sphere
and the hemispheres, and the outside surface of the beryllium was
plated with nickel to seal the polonium in the source. The source
contained approximately 2 curies of polonium and emitted $4.86 \pm 0.40 \times 10^6$
neutrons per second on November 26, 1949, according to a calibration
performed at Los Alamos. Since the source decayed with a half life of
140 days, the data obtained was corrected to the value which would
have been obtained on the calibration date.

The pairs observed from this source have been plotted in figure
5, as obtained from a 31 mg/cm$^2$ tin radiator. The data has been corrected
for accidental counts with a rate about 3% of the maximum counting rate,
and for a no-radiator background which was about 13% of the maximum pair
counting rate in the vicinity of the peak, and rose to about 40% of
the maximum pair rate in the vicinity of 3000 gauss- cm.

The observed maximum counting rate for pairs was 41.8 counts
per 1000 seconds per pair of counters, corrected to November 26, 1949.
The maximum rate occurred for $H \phi = 6880$ gauss-cm, and the width at half
maximum was observed to be 11.9%. The peak shift may be calculated to
be 4.9%, giving an observed gamma ray energy of $4.45 \pm 0.09$ Mev. No
other gamma rays have been observed with this spectrometer, but the
sensitivity is very low below the 4.45 Mev line, so that gamma rays in
this region are not ruled out.

We may make an approximate calculation of the counting efficiency
from the published measurements of the gamma ray and neutron yields of
PAIR SPECTRUM FROM POLONIUM BERYLLIUM

SOURCE

USING 31.0 mg/cm² TIN RADIATOR
this source. The yield of neutrons has been measured by Roberts, by Segre and Wiegand, and by Halpern (see discussion in Ha49) to be, respectively, 77, 73, and 50 x 10^-6 neutrons per polonium alpha. Bothe and Becker estimated the yield of gamma radiation to be about 35 x 10^-6 quanta per polonium alpha particle. Within the limits of accuracy of these measurements, there are 2 neutrons for each gamma quantum. Knowing the strength of this source to be 4.86 x 10^6 neutrons per second, we can estimate the gamma ray strength as 2.4 x 10^6 quanta per second. This number of quanta would be equivalent to the gamma radiation from 0.066 milligrams of radium in equilibrium, not considering very low energy gamma rays. A comparison of this source with radium, using a geiger counter sheathed with \( \frac{1}{2} \) inch of lead, indicated a counting rate equivalent to that of 0.22 milligrams of radium. This does not seem to be in serious disagreement with the data quoted above, considering the increased efficiency of the Geiger counter for the higher energy gamma rays of the polonium-beryllium source. If we assume, then, that there are 2.4 x 10^6 quanta per second, all of 4.45 Mev, we find that this pair spectrometer counts one pair (per unit channel weight) for 5.8 x 10^7 gamma quanta emitted. This figure is of course only roughly determined. However, it indicates a sensitivity about 140 times as high as at 2.62 Mev, and about seven times lower than that calculated theoretically for 9.1 Mev, using the same radiator of 31 mg/cm^2 tin.

The large decrease in sensitivity in going from 4.45 Mev to 2.62 Mev indicates that the 2.7 Mev gamma ray reported by several observers (Bo36a, Dz39) probably would not be detected if present. Statistical
fluctuations in the region of 2.7 Mev are of the order of 3% of the maximum counting rate; considering the change in sensitivity, it seems probable that a 2.7 Mev gamma ray of intensity somewhat higher than that at 4.45 Mev would not have been detected. However, there is definite evidence that no higher energy gamma radiation is present. Statistical deviations amount to about 1% of the peak yield in the region between 6 and 8 Mev, and a consideration of the increase in efficiency would cut the maximum intensity which might not be detected to about 4/3 of the 4.45 Mev gamma ray strength.

The polonium-beryllium has also been observed with a much thicker radiator, partly to observe the effect of such a radiator. The results, plotted in figure 6, do not disagree with those obtained with the thin radiator. The radiator used was 273 mg/cm² tungsten, about 340 kilovolts thick as compared to 42 kilovolts for the 31 mg/cm² tin target used in most of this work. Though the pair production cross section should be 12.4 times larger in this thick radiator, the actual yield observed (74 counts per 1000 seconds per unit channel weight) was only 77% higher. The figure 74 is the height of the peak above a wide, low background. This background is proportionately higher than for the thin target by the ratio of target thicknesses (8.8), so that it is probably due to the same causes--scattered pairs, Compton-gamma coincidences, etc.

The half width of the thick radiator distribution, above the base, is 18.7%; applying the usual formula, we find that the peak shift correction should be 8.7% or 3.8% more than for the thinner radiator. The peak does not appear to be shifted by this much; it is near 6800
PAIR SPECTRUM FROM POLONIUM BERYLLIUM

SOURCE

USING 273 mg/cm² TUNGSTEN RADIATOR
gauss-cm, as far as can be ascertained, although the statistics do not allow it to be as accurately located as in the case of the more careful thin-radiator determination. The extra 3.8% shift should put the peak at 6640 gauss-cm, but the marked asymmetry of the line casts doubt on the validity of this correction, as has been pointed out previously.

This thick-radiator data does give us definite information as to the absence of gamma radiation up to 11 Mev, as is obvious from figure 6. Any overlooked gamma rays in this region would have to have extremely small intensities, much less than 1% of the 4.45 Mev intensity.

C: Boron Bombarded with Deuterons. In order to clarify previous work, the gamma ray spectra from boron isotopes bombarded with deuterons were investigated. Thick targets of B$_2$O$_3$, fused onto silver backing, were bombarded with 1.56 Mev deuterons from the Rice Institute Van de Graaff generator. The two targets used contained natural boron (18.8% B$^{10}$, 81.2% B$^{11}$) and B$^{10}$ obtained from Oak Ridge National Laboratory (96% separated). The deuterons were magnetically analyzed, and the deuteron beam current was measured by a current integrator which produced one register count for 0.0801 microcoulombs, or 5.00 x 10$^{11}$ deuterons. The results obtained for these two targets, using the same 31.0 mg/cm$^2$ tin radiator, are plotted in figures 7 and 8. Small corrections have been made for non-radiator background and for accidental coincidences. Standard deviations are shown for each point possible, except that in some cases the deviation lies within the area covered by the point. The ordinate units are pair counts per 1000 integrator counts, divided by the channel weight. The beam current was generally about 0.25 micro-
PAIR SPECTRUM FROM BOMBARDMENT OF

96% B^{10} (THICK TARGET OF B_{2}O_{3}) WITH 1.56 MEV

DEUTERONS, USING 31.0 mg/cm^{2} TIN RADIATOR (ARBITRARY

UNITS, SAME AS FOR FIGURE 8)
PAIR SPECTRUM FROM BOMBARDMENT OF
NATURAL BORON (THICK TARGET OF B$_2$O$_3$) WITH 1.56 MEV DEUTERONS, USING 31.0 mg/cm$^2$ TIN RADIATOR (ARBITRARY UNITS, SAME AS FOR FIGURE 7)
amperes, so that about 3 integrator counts were obtained per second. Each point on the graph except for a few on the ends, represents the weighted average of four determinations, one in each channel, each determination being taken for 1000 integrator counts, or about 300 seconds. The no-radiator background was measured in the same way, except that fewer determinations were made in regions where the no-radiator background was almost negligible. Each of these curves took eight or ten hours of running time, not including the shorter time needed to measure the background as a function of $HP$. The highest point in these two curves represents about 1800 counts, and the other points represent numbers of counts proportionate to their heights.

In each of these two spectra the same three strong lines appear; the two upper lines are five times stronger in $B^{10}$ than in natural boron, indicating that they come from $B^{10}$ only. The lowest energy line had roughly the same intensity in both determinations, so that it must come from both isotopes. Because of the overlapping of the lines it is difficult to obtain the half width accurately except for the line of highest energy. In $B^{10}$ this line, with peak at 14,400 $HP$, has a width at half maximum of 11.7%, giving a peak shift of 4.8%. Since we found the peak shift for the 4.45 Mev polonium-beryllium line to be 4.9% in the same radiator, we may assume that a peak shift of 4.8% holds for all the lines in these spectra, and correct accordingly. None of the other half widths can be measured as accurately as this one. Using the 4.8% correction, we find that the lines in $B^{10}$ with peaks at 7000, 10600, and 14400 gauss-cm correspond to gamma ray
energies of 4.52, 6.74, and 9.11 Mev. The lines from natural boron have apparently identical energies, though the peaks cannot be located quite as accurately as in the separated isotope. The widths of the lines, estimated by allowing for the overlapping effects, and the heights in terms of pair counts per 1000 integrator counts per unit channel weight, are given in the following table:

<table>
<thead>
<tr>
<th>Target</th>
<th>Energy (Mev)</th>
<th>Pair Yield</th>
<th>Width of Line</th>
</tr>
</thead>
<tbody>
<tr>
<td>96% B\textsuperscript{10}</td>
<td>4.52 ± .10</td>
<td>38</td>
<td>17%</td>
</tr>
<tr>
<td></td>
<td>6.74 ± .13</td>
<td>110</td>
<td>15%</td>
</tr>
<tr>
<td></td>
<td>9.11 ± .18</td>
<td>141</td>
<td>11.7%</td>
</tr>
</tbody>
</table>

| 81% B\textsuperscript{11} | 4.5 ± .1     | 23         | 11%           |
|                           | 6.7 ± .2     | 24         | 15%           |
|                           | 9.1 ± .2     | 27         | 12%           |

The ratios of the yields from separated B\textsuperscript{10} and natural boron for the two high energy lines are 4.6 and 5.2, which are equal to the ratio of 96% to 1% of B\textsuperscript{10} within experimental error. There is thus no doubt that these two lines are due to the B\textsuperscript{10} isotope. Any radiation from the other isotope in this range is very weak, if present, and is completely obscured by the strong high energy rays of B\textsuperscript{10}.

Calculating the yield, in the same units, that would be obtained using 100% separated boron isotopes, we obtain:
<table>
<thead>
<tr>
<th>Target</th>
<th>Energy (Mev)</th>
<th>Pair Yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{10}$B</td>
<td>4.52 ± .10</td>
<td>39</td>
</tr>
<tr>
<td>$^9$B</td>
<td>6.74 ± .13</td>
<td>115</td>
</tr>
<tr>
<td>$^9$B</td>
<td>9.11 ± .18</td>
<td>147</td>
</tr>
<tr>
<td>$^{11}$B</td>
<td>4.5 ± .1</td>
<td>19</td>
</tr>
</tbody>
</table>

The two lower energy lines in the $^{10}$B spectrum seem to be unusually wide, the upper energy side being wider than the lower energy side, even after subtraction of the estimated overlapping effects. In the case of the lowest line it is probable that the width can be accounted for as due to errors in estimating the overlapping effect of the next higher line, and as due to statistical errors. This does not seem to be so likely an explanation of the shape of the 6.73 Mev line, though it is not impossible.

In order to make sure that the 4.5 Mev gamma ray actually came from both boron isotopes and not from some other element, a check was made on the pair spectrum from a thick target of boron carbide. This spectrum was not measured as accurately as the other spectra; only a few of the points were overlapped, and the no-radiator background was not measured. The resulting pair spectrum, allowing for the unsubtracted background, appeared to be identical with the spectrum from normal boron oxide, except that the yield was approximately 1.6 times as large for each of the three prominent lines. This difference is to be expected, because of the larger percentage of boron atoms in the boron carbide.
We may estimate the true yield of these gamma rays by making use of the spectrometer efficiency values we have calculated for a 31 mg/cm$^2$ tin radiator. Guessing at the interpolation between the efficiency found (roughly) for the 4.45 Mev polonium-beryllium gamma ray, and the approximately calculated value for a 9.1 Mev gamma ray, we arrive at the following results, which are in terms of the yield for thick elemental boron targets of 100% separated isotopes:

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Gamma Ray Energy (MeV)</th>
<th>Pair Counts per Integrator Count</th>
<th>Gamma Quanta per Pair Count Microcoulomb in 31 mg/cm$^2$Sn</th>
</tr>
</thead>
<tbody>
<tr>
<td>B$^{10}$</td>
<td>4.52 ± .10</td>
<td>.096</td>
<td>6 x 10$^7$ $\sim$ 7.2 x 10$^7$</td>
</tr>
<tr>
<td></td>
<td>6.74 ± .13</td>
<td>.288</td>
<td>2 x 10$^7$ $\sim$ 7.2 x 10$^7$</td>
</tr>
<tr>
<td></td>
<td>9.11 ± .18</td>
<td>.368</td>
<td>0.8 x 10$^7$ $\sim$ 3.7 x 10$^7$</td>
</tr>
<tr>
<td>B$^{11}$</td>
<td>4.5 ± .1</td>
<td>.048</td>
<td>6 x 10$^7$ $\sim$ 3.6 x 10$^7$</td>
</tr>
</tbody>
</table>

Although the values of the spectrometer efficiency, in terms of the pair counts per gamma quantum, cannot be justified except as rough interpolations between two approximately known values, the resulting absolute yield values, in gamma quanta per microcoulomb of deuterons, are probably not in error by as much a factor of four.

Rough measurements of the intensity of gamma radiation from deuteron bombardment of the two targets used, by comparison with radium gamma radiation, making use of a small Geiger counter sheathed in $\frac{1}{2}$ inch of lead, indicated that the B$^{10}$ target was equivalent to 8 milligrams of radium, per microampere of deuterons, and the normal boron target was equivalent to 5 milligrams of radium per microampere. Making
a crude estimate as to the counter efficiency at the various energies involved, we find that approximately $7 \times 10^7$ gamma quanta per microcoulomb are obtained from the $^{10}_B$ target and about $4 \times 10^7$ quanta per microcoulomb are obtained from normal $B_2O_3$. This does not seem to be inconsistent with the intensity values estimated in the above table, considering the uncertainties involved.

Results indicate that there is no gamma radiation above approximately 10 Mev from deuteron bombardment of $^{10}_B$. In the region from 11.5 to 15 Mev statistical fluctuations from the zero line are of the order of 0.5% of the pair counting rate at 9.11 Mev. Taking into account the increased pair cross section in this energy range, we can estimate the upper limit of possible gamma radiation in this range as being a few tenths of 1% of the intensity at 9.11 Mev. We cannot say the same about $^{11}_B$, because of larger statistical fluctuations in the data.
CHAPTER VIII

DISCUSSION OF THE EXPERIMENTAL RESULTS

The polonium-beryllium spectrum, from the reaction $\text{Be}^9(\alpha,n)\text{C}^{12}$, has been found to consist of a single gamma ray of energy $4.45 \pm 0.09$ Mev, with the possibility of radiation at lower energy remaining because of the decrease in sensitivity of the spectrometer below this energy. This removes one of the important bits of evidence for the 7.1 Mev level in $\text{C}^{12}$. The evidence for the 2.7 Mev gamma ray from the same reaction is not clearcut, for the same statistical reasons which threw some doubt on the 7 Mev line. However, the data presented here should not be regarded as proof of the non-existence of the line, for the spectrometer would probably not have detected it. If the 2.7 Mev line exists, then the 7 Mev level is necessary, for there seem to be no levels in $\text{C}^{12}$ below 4.45 Mev, from all available evidence. We should, then, consider more carefully the evidence for this 7 Mev level. This evidence has been partially discussed in an earlier section of this thesis. We have seen that neither the neutron groups from $\text{Be}^9(\alpha,n)\text{C}^{12}$ nor the gamma excitation threshold in the same reaction can be considered as good evidence for such a level.

The reaction $\text{N}^{14}(d,\alpha)\text{C}^{12}$, with $Q = 13.50$ Mev, leads to various levels in $\text{C}^{12}$. Holloway and Moore, (Ho40) bombarding enriched mixtures of nitrogen isotopes with 1 Mev deuterons, observed $\alpha$ groups from $\text{N}^{14}$ leading to $\text{C}^{12}$ levels at 4.37 and 7.62 Mev. The latter group was weak,
but seemed definitely to be associated with \( ^{14}\text{N} \) rather than with \( ^{15}\text{N} \).

Guggenheimer, Heitler, and Powell, \( (\text{Gu}47) \) bombarding gaseous nitrogen with 6.5 Mev deuterons, observed alpha groups leading to these same levels. This work does not have the statistical accuracy which Holloway and Moore attained; the group associated with the 7 Mev level in \( ^{12}\text{C} \) was slightly doubtful.

On the other hand, Malm \( (\text{Ma}50) \) performed a magnetic analysis on the \( \alpha \) particles from this reaction, finding three groups, corresponding to the ground state of \( ^{12}\text{C} \) and to excited levels at 4.485 and 9.667 Mev (\( \pm 20 \) kev), but found no sign of any group corresponding to a level at 7 Mev, to about 10\% of the intensity.

Gamma ray lines have been observed from nitrogen under deuteron bombardment; Gaerttner and Pardue \( (\text{Ga}40) \) found lines at 2.2, 4.2, 5.3\( \pm 0.4 \), 7.2\( \pm 0.4 \), and \( \sim 11 \) Mev. The second and fourth lines may be assumed to come from the \( ^{14}\text{N}(d\alpha)^{12}\text{C} \), but the fourth one may equally well be assigned to the reaction \( ^{14}\text{N}(dp)^{15}\text{N} \) \( (Q = 8.57) \).

Thus, at present, there is some doubt as to whether a 7 Mev level in \( ^{12}\text{C} \) is excited in the \( ^{14}\text{N}(d\alpha)^{12}\text{C} \) reaction.

The bombardment of natural boron with deuterons has long been known to produce several high energy gamma rays. Gaerttner, Fowler, and Lauritsen, \( (\text{Ga}39) \) bombarding with 550 to 850 kilovolts peak voltage, found gamma rays of 1.5, 2.2\( \pm 0.3 \), 4.4\( \pm 0.3 \), 6.9\( \pm 0.4 \) Mev, with relative intensities of \( \geq 2.5 \), \( \sim 2.5 \), 1.0, 0.3, and 0.1.

Halpern and Crane, \( (\text{Ha}39) \) bombarding with deuterons of 700 kilovolts maximum energy, found lines of 1.4, 2.4, 4.2, 6.0, and 9.1 Mev, with
relative intensities of 1,1,6,2, and 1. Aside from some variation in the intensities the two sets of data agree very well. There are several possibilities for the assignment of the lower energy gamma rays, particularly because of the presence of two isotopes of boron. In general, however, the two highest energy lines, and part of the 4.2 Mev line, were assigned (Ho48) to levels in C^{12} due to the B^{11}(d,n)C^{12} reaction (Q = 13.78 Mev). This was done partly because of the "well known" nature of the 7 Mev level in C^{12}. As the present work shows, these gamma rays should have been assigned to the other isotope of boron.

The work of Gibson (Gi49) seemed to give proof that the 7 Mev level of C^{12} was excited in the B^{11}(d,n)C^{12} reaction. Using separated isotopes, he observed the neutron energies from proton tracks in photographic plates; he found a weak group from B^{11} corresponding to the 7 Mev level of C^{12}, as well as strong groups corresponding to the 4.47 and 9.72 Mev levels. A strong neutron group of nearly the same energy as the weak group from B^{11} was produced from B^{10}. Gibson might have assigned this group to B^{10} contamination, except that its energy fell just slightly too low to be accounted for by statistical considerations. However, the strong groups from B^{11} were observed as weak groups in B^{10}, with energy falling slightly too low. This was explained as due to the fact that the contaminating isotope was not on the target itself, but on the target holder. This explanation might account for the same phenomenon in B^{11}. As a matter of fact, analysis of the intensities of all the groups appearing from targets of separated B^{10}, separated B^{11}, and natural boron leads to the conclusion that, if the B^{10} and B^{11} are,
respectively, 96% and 95% separated, the intensity of the small peak in the B\textsuperscript{11} spectrum is just accounted for by the B\textsuperscript{10} contamination and the intensity of the contamination lines in the B\textsuperscript{10} spectrum is explained. Hence it appears that no 7 Mev level in C\textsuperscript{12} is excited in the B\textsuperscript{11}(d,n)C\textsuperscript{12} reaction. The work of Bonner and Brubaker (Bo36) has been discussed previously; they assigned the neutron groups to the correct isotopes, though unseparated isotopes were used.

It seems that the existence of a level in C\textsuperscript{12} in the neighborhood of 7 Mev is at least doubtful, particularly in view of the results obtained with this pair spectrograph.

Fulbright and Bush, (Fu48) studying the inelastic scattering of protons from light nuclei, at proton energies of 12.3 and 15.0 Mev, found groups corresponding to levels in C\textsuperscript{12} at 4.4 \pm 0.2, 5.5 \pm 0.3, and 9.7 \pm 0.6 Mev. the intensities being respectively strong, medium, and weak. The targets used were lampblack and soot from burning camphor, deposited on platinum. The two strong groups from oxygen corresponded to levels in O\textsuperscript{16} at 5.8 \pm 0.3 and 6.7 \pm 0.3 Mev, and there is some slight possibility that the group from the new 5.5 Mev level in C\textsuperscript{12} should be assigned to oxygen contamination. The other levels found check with known levels in C\textsuperscript{12}. This 5.5 Mev level in C\textsuperscript{12} was not confirmed by the inelastic proton scattering data of Levinthal, Martinelli, and Silverman, (Le50) at 16 and 32 Mev. Using a polystyrene target, they found only groups corresponding to 4.8 and 10.1 Mev levels in C\textsuperscript{12}.

There are several reactions which might account for the 4.5 \pm 0.1
Mev gamma ray line observed from B\textsuperscript{11}+D with the pair spectrograph.

These are:

1. \( B^{11}(d,\alpha)B^{9} \), \( Q = 8.03 \text{ Mev} \)
2. \( B^{11}(d,p)B^{12} \), \( Q = 1.2 \text{ Mev} \); \( B^{12}\rightarrow C^{12} \), \( Q = 13.4 \text{ Mev} \)
3. \( B^{11}(d,n)C^{12} \), \( Q = 13.78 \text{ Mev} \).

As to the first reaction, a level at 4.8 Mev has been found (Bj38) in Be\textsuperscript{9}, but alpha particles from reaction (1) have not been observed from this level.

The second and third reactions lead to the same levels in C\textsuperscript{12}; however, the second reaction apparently does not have the intensity (Hu49, Ho50) to account for the amount observed with the pair spectrograph.

The third reaction is certainly the cause of much if not all of the 4.5 Mev gamma rays observed, particularly in view of the by now well confirmed level in C\textsuperscript{12} at about this energy.

It is possible that other gamma rays of higher energy are produced in these reactions. If so, they are obscured by the strong radiation from the B\textsuperscript{10} isotope. Some of the fluctuations observed at the high energy end of the natural boron spectrum may be due not to statistics but to other gamma rays from the bombardment of B\textsuperscript{11} with deuterons. Levels (Ho48) are thought to exist in C\textsuperscript{12} at 9.5 Mev, and possibly at 10.3 and 10.8. Such levels could be excited by the B\textsuperscript{11}(d,n) reaction.

There are also several reactions which may account for the gamma rays from B\textsuperscript{10}+D. These are:
(1) \( ^{10}B \, (d,n)^{11}C \), \( Q = 6.53 \text{ Mev} \)

(2) \( ^{10}B \, (d,\alpha)^{8}Be \), \( Q = 17.81 \text{ Mev} \)

(3) \( ^{10}B \, (d,p)^{11}B \), \( Q = 9.24 \text{ Mev} \)

There is enough energy available in reaction (1) to produce all but the highest energy gamma rays; however, the only level observed in \(^{11}C\) has been located at 2.1 Mev; \((\text{Bo}36, \text{Gi}49)\) this reaction may produce 2.1 Mev gamma rays from this level. These gamma rays were of course not observed with this pair spectrometer.

The second reaction is exoergic enough to account for all of the gamma rays. Levels have been found in \(^{8}Be\) at 4.8, 7.0, and 9.8 Mev, in addition to higher and lower levels \((\text{Be}48)\). None of these levels are known to produce gamma rays except for the 4.8 Mev level, in the Li\(^7\)(d,n) reaction.\((\text{Be}47)\) These levels seem to be slightly higher than would seem to fit the gamma ray energies measured from the \(^{10}B\,d-D\) reactions.

The most probable source of the gamma rays is the \(^{11}B\) nucleus. Cockcroft and Lewis \((\text{Co}36)\) found the \(^{10}B\,(d,p)^{11}B\) reaction to have six times the cross section of the \(^{10}B\,(d,\alpha)^{8}Be\) reaction, bombarding at 0.57 Mev. The levels observed in magnetic analysis of the protons from reaction (3) seem to fit closely the measured gamma ray energies. W. O. Bateson \((\text{Ba}50)\) observed levels in \(^{11}B\) at 2.21, 5.08, 6.96, 7.83, and 8.60 Mev, using separated \(^{10}B\) and 3.8 Mev deuterons. The most recent and complete work on the magnetic analysis of the protons, by Van Patter and Buechner,\((\text{Va}50)\) gives the following (tentative) values for the relative intensities of the proton groups and the associated
energy levels in $^8{\text{B}}$, at 1.5 Mev deuterom energy:

<table>
<thead>
<tr>
<th>Energy Level (Mev)</th>
<th>Relative Intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1.0</td>
</tr>
<tr>
<td>2.141 ± .014</td>
<td>0.2</td>
</tr>
<tr>
<td>4.457 ± .013</td>
<td>0.6</td>
</tr>
<tr>
<td>5.033 ± .013</td>
<td>0.4</td>
</tr>
<tr>
<td>6.752 ± .013</td>
<td>0.9</td>
</tr>
<tr>
<td>(6.802 ± .013) (?)</td>
<td>0.1</td>
</tr>
<tr>
<td>7.297 ± .012</td>
<td>0.6</td>
</tr>
<tr>
<td>8.565 ± .012</td>
<td>0.15</td>
</tr>
<tr>
<td>8.921 ± .012</td>
<td>3.4 (?)</td>
</tr>
<tr>
<td>9.186 ± .012</td>
<td>5.3 (?)</td>
</tr>
<tr>
<td>9.270 ± .012</td>
<td>2.1 (?)</td>
</tr>
</tbody>
</table>

The last three groups were observed under different experimental conditions, and it is believed (Va50) that the intensities given are somewhat in error, and probably too high.

It will be noticed that these energies and intensities fit fairly well the gamma ray energies and intensities observed in the present work. The two weakest levels, at 6.802 and 8.565 Mev, would not be detectable in the gamma ray spectrum if at these intensities. The line at 2.141 Mev would not be detected because of the extreme insensitivity of a pair spectrometer at this energy. If gamma ray lines existed with energies of 5.033 Mev and 7.297 Mev and with slightly lower intensity than that given, they would account for the asymmetry of the two lowest energy gamma ray lines observed with the pair spectrometer (4.52 and 6.74 Mev).
There is of course a possibility that the three proton groups in the vicinity of 9 Mev are represented by three closely spaced gamma ray lines, which would not be resolved in the pair spectrometer.

Thus the proton and gamma ray spectra seem to be in reasonable agreement, and we may conclude that they probably correspond to the same levels in $^B_{11}$.

The intensities observed with this pair spectrometer also check well with the integrated gamma ray intensity observed by G. C. Phillips (unpublished). He observed a cross section of $0.46$ barns for gamma radiation produced by 1.56 Mev deuterons on $B_2O_3$ and an integrated yield of about $7.5 \times 10^7$ quanta per microcoulomb in a thick target at 1.56 Mev. This would amount to approximately $19 \times 10^7$ quanta in a target of pure boron. The sum of the intensities estimated for the $B^{10} \rightarrow D$ gamma rays from the pair spectrometer work is about $20.1 \times 10^7$ quanta per microcoulomb. This of course takes in no gamma rays of energy less than 4.52 Mev and should be increased slightly to account for the 2.1 Mev gamma ray. Evidently the determination of gamma ray intensity performed in these two different ways gives closely similar results.
ACKNOWLEDGEMENTS

I wish to thank Professor T. W. Bonner for guidance and assistance in all phases of this work. I am grateful to Dr. G. C. Phillips for sharing to a large extent in the work with boron isotopes, and for much helpful advice. I am indebted to W. H. Burke and J. J. Banewicz for assistance in chemical phases of this work, and to S. J. Bame and L. M. Baggett for the construction of the magnet current regulator. Indispensable to this work was the skilful instrument work of Messrs. Van der Henst, de Vries, Belcher, and Harmony. The loan of the polonium-beryllium source by the Los Alamos Scientific Laboratory made possible an important portion of this work.

For financial assistance in the form of Fellowships I am indebted to the Rice Institute and to the Atomic Energy Commission; this work was supported by the joint program of the Atomic Energy Commission and the Office of Naval Research.
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