RING FOCUS DETECTION IN A THIN LENs NUCLEAR SPECTROMETER

by

Donald Chesley Milley

A THESIS SUBMITTED IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF APPLIED SCIENCE

in the Department of PHYSICS

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

Members of the Department of PHYSICS

THE UNIVERSITY OF BRITISH COLUMBIA

April, 1955
ABSTRACT

A thin lens nuclear spectrometer has been modified by the use of ring focus detection. The transmission of this spectrometer has been increased by a factor of 6 with no appreciable loss in resolution.

An examination of the beta spectrum of Eu$^{152,154}$ has been carried out with this instrument. Internal conversion lines of 74.6, 115.5, 198.3, 242.7, 295.9 and 339.8 Kev were found. These lines have been assigned to a 122 Kev transition in Sm or a 124 Kev transition in Gd, a 245 Kev transition in Sm and a 346 Kev transition in Gd. The K-to-L ratios of the 245 and 346 transitions have been measured and were found to be 2 and 4 respectively. A Fermi plot of the beta spectrum has been made and endpoints of 1450, 1060 and 675 Kev were found. Also, some indication of a lower energy beta group was found. Estimates of the comparative lifetimes of the 1450, 1060 and 675 Kev beta transitions place all of them as second (or higher) forbidden.
ACKNOWLEDGEMENTS

The work described in this thesis was supported by a Grant-in-Aid-of-Research allotted to Dr. K. C. Mann by the National Research Council of Canada.

I am indebted to Dr. Mann for much advice and assistance given throughout the course of this work.

I am grateful to the British Columbia Telephone Company for the award of a scholarship.

Acknowledgement is made also to Mr. G. W. McMahon for the conventional thin lens spectrometer measurements of the Sb$^{124}$ spectrum, and to Mr. W. Morrison for his technical assistance.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th></th>
<th>INTRODUCTION</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>II</td>
<td>MODIFICATION OF THIN LENS SPECTROMETER</td>
<td>23</td>
</tr>
<tr>
<td></td>
<td>A. Previous Modification</td>
<td>23</td>
</tr>
<tr>
<td></td>
<td>B. Subsequent Modification</td>
<td>29</td>
</tr>
<tr>
<td>III</td>
<td>INVESTIGATION OF Eu$^{152,154}$</td>
<td>40</td>
</tr>
<tr>
<td></td>
<td>A. Previous Investigation</td>
<td>40</td>
</tr>
<tr>
<td></td>
<td>B. Current Investigation</td>
<td>42</td>
</tr>
<tr>
<td></td>
<td>REFERENCES</td>
<td>50</td>
</tr>
<tr>
<td>Figure</td>
<td>Illustration Description</td>
<td>Page</td>
</tr>
<tr>
<td>--------</td>
<td>--------------------------</td>
<td>------</td>
</tr>
<tr>
<td>1.</td>
<td>An Example of a Decay Scheme</td>
<td>3</td>
</tr>
<tr>
<td>2.</td>
<td>An Example of a Beta Spectrum</td>
<td>3</td>
</tr>
<tr>
<td>3.</td>
<td>An Example of a Fermi Plot</td>
<td>3</td>
</tr>
<tr>
<td>4.</td>
<td>The Definition of Resolving Power</td>
<td>14</td>
</tr>
<tr>
<td>5.</td>
<td>Spectrometer of Von Bayer and Hahn</td>
<td>14</td>
</tr>
<tr>
<td>6.</td>
<td>Main Features of π Spectrometers</td>
<td>14</td>
</tr>
<tr>
<td>7.</td>
<td>Main Features of Helical Spectrometers</td>
<td>17</td>
</tr>
<tr>
<td>8.</td>
<td>Electron Trajectories of Thin Lens Spectrometer</td>
<td>17</td>
</tr>
<tr>
<td>9.</td>
<td>The Modified Spectrometer</td>
<td>25</td>
</tr>
<tr>
<td>10.</td>
<td>Original Detector</td>
<td>26</td>
</tr>
<tr>
<td>11.</td>
<td>Effect of Discriminator on Significant Counts</td>
<td>31</td>
</tr>
<tr>
<td>12.</td>
<td>Modified Detector</td>
<td>34</td>
</tr>
<tr>
<td>13.</td>
<td>Portion of Beta Spectrum of Sb(^{124})</td>
<td>36</td>
</tr>
<tr>
<td>14.</td>
<td>Decay Scheme of Eu(^{152,154})</td>
<td>41</td>
</tr>
<tr>
<td>15.</td>
<td>Measured Beta Spectrum of Eu(^{152,154})</td>
<td>42</td>
</tr>
<tr>
<td>16.</td>
<td>Portion of Fermi Plot for Energies Greater than 360 Kev.</td>
<td>44</td>
</tr>
<tr>
<td>17.</td>
<td>Beta Groups of Eu(^{152,154})</td>
<td>45</td>
</tr>
</tbody>
</table>
I

INTRODUCTION

Nuclear spectroscopy is the study of the energy states of nuclei by the direct measurement of the energies and intensities of the radiations from these nuclei. These radiations may be either particles (electrons) or photons (gamma-rays). The interpretation of these measurements gives information on the energy states of the nuclei involved. These interpretations are discussed below, but to summarize we may say that the basic problem is to obtain information on (1) the sequence of emission of particles, (2) the energies of the states from which radiation occurs, (3) the angular momentum or spin of each energy state in terms of the quantum unit ħ and (4) the parity of each state (parity is a symmetry property of the wave function of the nucleus). When such information is correlated, we have what is described in the literature as the decay scheme of nucleus. Such schemes provide a means whereby nuclear theories may be tested. In some instances, they provide a basis on which modifications to the present theory may be made.

Most nuclear spectroscopy is performed using
magnetic analysis of the momenta of electrons emitted in the decay process. More recently, the development of the scintillation counter with pulse height selection has added a powerful tool for this work. In what follows a description of the main ideas in nuclear decay will be given, as well as a survey of the more common techniques of analysis.

An unstable, or radioactive, nucleus may decay in a number of different ways. We are interested, in this field, in those cases where the nucleus emits a negative or positive electron, thereby changing the nuclear charge by an electronic unit. This type of decay is known as beta-decay. It is customary to represent the relative energies or masses ($E = M_0c^2$) in the manner indicated in figure 1. The discrete energy states of nuclei are shown as horizontal lines, the vertical displacement corresponding to the energy of the state measured from its lowest or ground state. The methods of decay are indicated by arrows between the energy levels. Figure 1 illustrates a decay process in which the parent nucleus ($Z$) decays to the ground state of the daughter nucleus ($Z + 1$) by two different routes. One route is by electron emission ($\beta^-$) to an excited state of the daughter and then by gamma emission to the ground state. The other route is by electron emission directly to the ground state of the daughter nucleus. Considering the law of conservation of energy and that the beta-decay
is between discrete energy levels, we would expect the electrons to be emitted with discrete energies corresponding to the energy difference between the levels involved. However, this is not the case.

If the radiations depicted in figure 1 are examined by means of a beta-ray spectrometer, the shape of the momentum spectrum would be as shown in figure 2. The electrons are not emitted with discrete energies, but rather they are emitted with continuous momentum, and hence energy, distribution. Experimental evidence shows that the end point of this distribution corresponds to the energy difference between the levels involved in the decay.

This apparent contradiction of the conservation of energy law is resolved in a detailed theory of beta disintegration by Fermi. He assumed, on the suggestion of Pauli, that the nucleus decayed by the simultaneous emission of two particles, the electron and a particle of essentially no mass or charge, the neutrino. The energy of the transition is shared between these two particles so that the greater the electron energy the less the neutrino energy. Since the neutrino has no charge and zero or a very small mass, it is difficult, if not impossible, to detect.

The maximum beta energy is difficult to determine from the momentum spectrum found experimentally since the curve approaches the momentum axis tangentially. This
PARBMT

DAUGHTER,

I AM EXAMPLE OF A DECAY SCHEME

COUNTING RATE

MOMENTUM

Figure 1  An Example of a Decay Scheme

Figure 2  An Example of a Beta-Spectrum

Figure 3  An Example of a Fermi Plot
difficulty may be overcome by examining the theoretical momentum distribution as given by the Fermi theory of beta-decay.

This distribution function has the form, in the majority of cases, of

\[ N(p) \propto F(\text{Emax} - E)^2 p^2 \]  

(1)

where \( N(p) \) is the number of beta particles emitted per unit time in the interval \( dp \) at \( p \),

\( p \) is the momentum of the beta particle,

\( F \) is a complex function which corrects for the effect of the Coulomb field of the nucleus on the emitted beta particle - this function is called the Fermi function and has recently been tabulated²,

\( E \) is the energy of the beta particle,

and \( \text{Emax} \) is the total energy involved in this transition. Then, if \( \sqrt{\frac{N}{p^2 F}} \) is plotted against \( E \), a straight line is to be expected, (figure 3), the intercept of this curve with the energy axis being \( \text{Emax} \). If more than one beta group is present, the second distribution may be obtained by a subtraction from the composite curve, assuming each group is independent of the others. This method of analysis is known as a Fermi plot. For more complex decay schemes the experimental errors accumulate with an increasing number of subtractions and hence the value of this type of analysis decreases.
Equation 1 is based upon the assumption that the spin change involved in the transition is \( \pm 1 \) or 0 with no parity change. The theory predicts that this is the most probable type of beta-decay. In analogy with optical nomenclature this is called an "allowed" transition, while those transitions in which there are higher spin changes with "YES" or "NO" parity changes are termed "forbidden". The shape of the Fermi plot is dependent on the spin and parity changes of the transition. For allowed transitions it is a straight line.

For first forbidden beta-decays (\( \Delta I = \pm 2, \pm 1, 0, \) YES) the Fermi plot is not straight. The shape of this distribution has been calculated\(^3\), and by the use of correction factors in the Fermi function it may be recognized and the spin and parity changes involved determined. Similarly for higher orders of forbiddenness.

The total probability that an excited nucleus will decay by beta emission may be written, for allowed transitions, as

\[
\lambda = \int P(p)dp
\]  

(2)

where \( \lambda \) is the total decay probability,

\( P_{\text{max}} \) is the maximum momentum corresponding to \( E_{\text{max}} \) above,

\( P(p)dp \) is the probability that the nucleus will decay with momentum \( p \) in the interval \( dp \).
and may be expressed as

$$P(p)dp = CF (E_{\text{max}} - E)^2 p^2 dp$$

(3)

where $C$ is a constant. (The other symbols are defined above.)

Equation (2) may be written as

$$\lambda = \int_0^{E_{\text{max}}} P(p)dp = C_f$$

where $f = \int_0^{E_{\text{max}}} F(E_{\text{max}} - E)^2 p^2 dp$. (4)

The reciprocal of the total decay probability has the dimensions of time and is known as the mean life, $\tau$, of the transition. Radioactive nuclei decay exponentially with time and the time required for one-half of the nuclei to decay is defined as the half-life, $T_{1/2}$, of the decay process. The half-life and the mean life are related by $\tau = \frac{T}{\ln 2}$.

From (4) we may write

$$\lambda = \frac{1}{\tau} = \frac{\ln 2}{T_{1/2}} = C_f \quad \text{or} \quad C = \ln 2 \frac{1}{f T_{1/2}}$$

(5)

The quantity $f T_{1/2}$ is termed the "comparative half-life" of the beta-decay. It is more convenient to deal with the logarithm of the comparative half-life. This last quantity has been related empirically with the forbiddenness of many beta-decays. It increases with the degree of forbiddenness. It is possible to obtain an indication of the degree of forbiddenness involved in a beta transition by comparison with the log ($f T_{1/2}$) values of transitions whose forbiddenness have been established by other measurements.
The daughter nucleus created by a beta-decay may be formed in an excited state. It may lose this excitation energy by ejecting an orbital electron or by emitting gamma radiation.

If the excited nucleus decays by emitting an electron, the electron will be mono-energetic with an energy equal to the energy difference between the levels involved less the binding energy of the orbital electron. These electrons are known as internal conversion electrons and the de-excitation process as internal conversion. Since the internal conversion electrons are mono-energetic, internal conversion is characterized experimentally by peaks superimposed on the beta spectrum (figure 2). The binding energy of the orbital electrons depends upon the orbit from which they originated. Hence, a series of peaks usually of decreasing intensity may be observed, all corresponding to the same energy transition but with the internal conversion electrons originating in the K, L, or M orbits.

If the excited nucleus decays by emitting gamma radiation, the gamma radiation will have an energy equal to the energy difference between the levels involved. Gamma radiation may not be studied directly with a magnetic spectrometer since the gamma-rays do not react with the magnetic fields. However, by allowing the gamma-rays to strike a thin foil of some high atomic number material,
orbital electrons may be ejected from the foil. It is the energy and intensity of these electrons which are studied by means of a magnetic spectrometer. These electrons are termed photo-electrons and the process as the photo-electric effect or external conversion. The foil is called the "radiator" and is generally some high Z material since the probability of photo-electron emission increases rapidly with the atomic number. The photo-electrons are mono-energetic for the same reason that internal conversion electrons are. The experimental spectrum obtained by studying the photo-electric effect is similar to an internal conversion spectrum in that there are several peaks corresponding to the same gamma-ray transition. The energy differences between the peaks of the same gamma-ray transition corresponds to the differences in binding energies between the orbital electrons of the radiator material.

These two processes, internal conversion and gamma emission, compete as methods by which a nucleus may de-excite. The probability that a nucleus will decay by internal conversion rather than by gamma emission increases rapidly with increasing spin change between the energy states involved in the transition. It also increases with decreasing transition energy and with increasing atomic number. A measure of this probability is the ratio of the number of internal conversion decays to the number of
competing gamma decays. This ratio is known as the internal conversion coefficient. These internal conversion coefficients have been calculated theoretically\(^6\), and a comparison between the experimental and the theoretical coefficients gives an indication of the spin and parity changes involved in the transition.

If \( \lambda \) is the total de-excitation probability and \( \lambda_{\gamma}, \lambda_{e} \) the probabilities of de-excitation by gamma emission and internal conversion respectively, then, since for one nucleus gamma emission and internal conversion are mutually exclusive,

\[
\lambda = \lambda_{\gamma} + \lambda_{e}
\]

The conversion coefficient is defined as:

\[
\lambda_e = \frac{\lambda_e}{\lambda_{\gamma}}
\]

A more general description of \( \lambda_e \) would be

\[
\lambda_e = \lambda_{ek} + \lambda_{el} + \lambda_em + \ldots
\]

where \( \lambda_{ek}, \lambda_{el}, \lambda_em \) are the probabilities that K, L or M orbit electrons are converted. This expansion of \( \lambda_e \) leads to the definition of

\[
\lambda_k = \frac{\lambda_{ek}}{\lambda_{\gamma}} \quad \text{as the K-conversion coefficient}
\]
\[
\lambda_L = \frac{\lambda_{el}}{\lambda_{\gamma}} \quad \text{as the L-conversion coefficient}
\]

and so on. Then \( \lambda \) may be written as

\[
\lambda = \lambda_k + \lambda_L + \ldots
\]
Theoretical calculations have been made of the values of the first six conversion coefficients for various transition energies, spin and parity changes, and for different Z values. The results of these calculations are tabulated. It is always difficult to accurately measure absolute intensities of any radiations in a spectrometer, since this presupposes an accurate knowledge of the efficiency of electron collection (i.e. the transmission factor) of the instrument. It is particularly difficult when attempting to measure gamma-ray intensities from photo-electron measurements since the probability of photo-electron emission varies with the gamma-ray energies. Also, there are variations in the preferred angles of emission from the source. However, the ratio of the number of K-conversions to the number of L-conversions can be measured, since presumably the collection efficiency is the same for both. This ratio is known as the K-to-L ratio and may be written symbolically as $\frac{K}{L}$. Theoretical calculations have been made of the value of this ratio for various transition energies, spin and parity changes, and for different Z values. The results of these calculations have been presented graphically and are available.$^7$

The probability that an excited nucleus will decay by gamma emission can be shown theoretically to be dependent upon the energy of the transition and the spin and parity changes involved. The reciprocal of this
probability is known as the lifetime of the excited state. Experimental measurements of these lifetimes have been carried out using very specialized electronic instruments. Such experiments yield further information on the spin and parity changes involved in such transitions. (e.g. - the work of Bell, Graham and Petch⁸.)

Some excited nuclei decay by the emission of two successive gamma radiations. The angular correlation between these gamma-rays or between beta and gamma-rays can be shown theoretically to be dependent upon the spin and parity changes involved. Experiments measuring these correlations have been carried out to determine the spin and parity changes. (e.g. - the work of Brady and Deutsch⁹.)

The recent development of scintillation counters and the improved techniques in pulse height selection have provided a powerful tool for the direct examination of the energy and intensity of gamma radiations. The amount of light produced by a gamma-ray in a scintillation crystal can be related to the energy of that gamma-ray. The amplitude of the output pulses from the scintillation counter is proportional to the light produced in the crystal, and hence can be related to the energy of the gamma-ray. By examining the pulse height spectrum by means of a pulse height analyser, measurements may be obtained of gamma-ray energies and relative intensities. This method of analysis has the advantage of high photon detection efficiencies.
The instruments most widely used for the experimental determination of the characteristics of the nuclear decay processes described above are beta-ray spectrometers. These instruments are capable of giving accurate measurements of beta-ray, internal conversion or photo-electric spectra. They are based on the fact that an electron moving through a uniform magnetic field, perpendicular to its motion, travels in a circular path.

The radius, \( \rho \), of this circular path is related to the momentum of the electron by the equation

\[
H\rho = \frac{mv}{e}
\]

where \( H \) is the magnetic field in gauss,
\( \rho \) is in cms.,
\( m \) and \( v \) are the mass and the velocity in c.g.s. units, and \( e \) is the electronic charge in e.m.u. units. The momentum \( \eta \), in units of \( m_0c \), is related to the magnetic hardness \( H\rho \), in gauss-cms., by

\[
H\rho = 1704.3\eta
\]

and to the energy \( \epsilon \), in units of \( M_0c^2 \), by the relativistic formula

\[
\eta^2 = \epsilon^2 - 1
\]

In practice, the conversion from \( H\rho \) to momentum or energy is carried out with the aid of tables.

Beta-ray spectrometers may be classified into two groups, the flat or \( \pi \) spectrometers, and the helical spectrometers. The helical spectrometers may be classified
into three types, the solenoidal, the thin lens and the thick lens. Magnetic spectrometers differ in the form in which the focusing is obtained, and in the source and counter arrangements. They are similar in that the electrons travel from the source to the counter through a variable magnetic field and that the electron paths are in a vacuum. All make use of an arrangement of stops or baffles to partly define the electron trajectories.

The important characteristics of any spectrometer are its resolving power and transmission. The ability of a beta-ray spectrometer to distinguish two groups of electrons of different momenta, such as two conversion groups, is termed the resolving power of the instrument. The measurement of the resolving power is usually made on a plot of a conversion spectrum. It is defined as the ratio of the peak width, in momentum, at half intensity to the momentum associated with the peak \( \frac{\Delta P}{P} \) (see figure 4). The fraction of all emitted particles from the source which reach the detector is termed the transmission of the instrument. Some workers in this field express the transmission as the ratio of the solid angle, measured at the source, from which the detected electrons came, to the total solid angle, \( 4\pi \).

In what follows a brief outline of the basic types of spectrometers will be given along with some of the modifications which have been made to increase either their transmission or resolving power.
The first beta-ray spectrometer was of the flat type and was developed by Von Baeyer and Hahn\textsuperscript{10} in 1910. The source was placed in a uniform magnetic field and the electrons, after describing an arc of less than $180^\circ$, were detected by a photographic plate (see figure 5). The electrons, which travelled in essentially one plane, produced lines on the photographic plate. From the position of these lines and a knowledge of the magnetic field, the momentum or energy corresponding to each line could be calculated. No attempt was made at this stage to focus the electrons, with the result that only those electrons with the same initial velocity and direction struck the photographic plate at the same place. A slit was placed in the electron path to limit the initial direction of the electrons. However, the geometry of such an arrangement necessitates that the line width on the photographic plate be greater than the slit width. For an improved line width, the slit width had to be decreased and this, in turn, decreased the transmission. This inverse relationship between the resolving power and the transmission is general for all beta-ray spectrometers and a compromise must always be made between these two properties.

In 1911, Danysz\textsuperscript{11} pointed out that if two circles with the same radius are drawn with their centers separated by a distance small with respect to the radius, they would
Figure 4. The Definition of Resolving Power

Figure 5. Spectrometer of Von Baeyer & Hahn

Figure 6. Main Features of $\pi$ Spectrometers
intersect at approximately diametrically opposite points. This mathematical property of circles was first utilized by Rutherford and Robinson\(^{12}\) in what was the first focusing magnetic spectrometer. Since electrons moving at right angles to a uniform magnetic field have circular trajectories, horizontal focusing was obtained by allowing the electrons to travel through a semi-circle before striking the photographic plate. The focus obtained by this method was not sharp since only two of the trajectories will intersect at one point (see figure 6). No attempt was made with this instrument at vertical focusing. The initial direction of the electrons was limited by a baffle as before but with the focusing property of the semi-circular path, the dispersion of the instrument was increased without any loss in transmission.

With photographic detection, the magnetic field remains constant and the electrons of different energies describe paths of different radii and reach the photographic plate at different places. Around 1928, Geiger-Mueller tubes replaced the photographic plates as a means of detection. With Geiger-Mueller tubes as detectors, fixed in position, the radius of the electron path is pre-determined and for any one field setting only electrons of one momentum will be detected. The field of the spectrometer can then be varied in discrete steps and the counting rate plotted against the momenta of the electrons giving the momentum
spectrum.

As pointed out above, the focussing achieved by semi-circular trajectories is not perfect. A number of modifications have been made to improve the transmission-resolving power relationship of $\pi$ spectrometers. In general this has been done by replacing the uniform field by a shaped one. In this manner, Siegbahn and Svartholm were able to increase the resolving power (by a factor of 2) for the same transmission. In their instrument, the electron describes an arc of $\pi \sqrt{2}$ radians in a field slightly decreasing to the exterior. This shaped field does introduce some vertical focussing, but its chief advantage is that electrons of greater momentum than those focussed travel in a weaker field and the radius of their path is then larger. Similarly, electrons of less momentum than those focussed travel in circular paths of smaller radii. This type of spectrometer is known in the literature as a double focussing spectrometer.

The solenoidal, the thin lens and the thick lens spectrometers have several similar properties. These spectrometers utilize the focussing property of an axially symmetric field for electrons emitted by a source located on the axis. The path of these electrons is a cylindrical helix, which is generally shown diagramatically as the projection of the path on a plane which is rotating with the path. The main features of helical spectrometers are shown
in figure 7.

The electrons leaving the source in the angle defined by the annular entrance baffle are approximately focussed on the axis at the detector. The exit baffle reduces the number of scattered electrons reaching the detector. The lead baffle on the axis of the spectrometer prevents direct gamma-rays from reaching the detector. If the source being examined emits both positive and negative electrons, or if the charge of the beta-particles is unknown, a helicoidal baffle (not shown) is placed in the middle section of the spectrometer. Since the trajectories of oppositely charged electrons rotate in opposite directions for any one direction of current in the magnet, selection of one type of electron may be achieved by this means. The helical spectrometers differ in the way in which the fields are produced. The field of a solenoidal spectrometer is a uniform axially symmetric field produced by means of a long solenoid. The field of a thin lens spectrometer is non-uniform, but axially symmetric, and is confined to a small region between the source and the detector. It is produced by a flat coil, usually iron free, concentric with the axis of the spectrometer chamber. The field of a thick lens spectrometer is non-uniform, but axially symmetric, and extends throughout the electron paths. It is produced by several coils aligned on the axis of the spectrometer.

These instruments do not produce a definite focus
Figure 7 Main Features of Helical Spectrometers

Figure 8 Electron Trajectories of Thin Lens Spectrometer
on the axis. Electrons which have the same momentum but which leave the source at different angles are focussed at different points along the axis. In analogy with optical nomenclature, this is termed "spherical aberration". The trajectories of these electrons cross over each other before they reach the axis. More will be said about this later.

The use of axially symmetric fields to focus electrons in beta-ray spectrometers was first proposed by Kapitza\textsuperscript{14} and later realized by Tricker\textsuperscript{15} in the form of a solenoidal spectrometer, the essentials of which have been described above. Later, Witcher\textsuperscript{16} found that by using an annular exit baffle instead of a circular one, the transmission-resolving power relationship could be improved. The annular baffle was placed in the region where the trajectories of the electrons being focussed had least separation.

The intersection of the electron paths corresponding to different initial angles constitutes an off-axis focus and because of the cylindrical symmetry of the spectrometer this is known as a ring focus. Upon the suggestion of Frankel\textsuperscript{17} the electron trajectories for a solenoidal spectrometer were calculated\textsuperscript{18} with emphasis on the optimum conditions under which full use of the ring focussing property could be made. Considerable improvement in transmission resulted from the application
of these calculations.

The chief advantages of a solenoidal spectrometer are: the uniform magnetic field makes possible rigorous analytical calculations of the electron paths; the adjustment of the instrument is easier to make; and the sensitivity to outside stray fields is less. The main disadvantages are that for use in measuring high energy spectra the dimensions of the instrument are large; and the electrical power requirements of the field are great.

The thin lens spectrometer was first built by Klemperer and later modified and used extensively by Deutsch, Elliott and Evans. It is customary to use iron-free coils in thin lens spectrometers since then the current in the coil is directly proportional to the momentum of the focussed electrons and one point calibration may be used. The trajectories of a thin lens spectrometer, unlike those of a solenoidal spectrometer, cannot readily be described by analytic expressions and must be calculated by the numerical integration of a differential equation.

Until 1949, when Hornyak, Lauritsen and Rasmussen made use of an annular exit baffle to increase the transmission of a thin lens spectrometer, the exit baffle had generally been formed by the window of the Geiger-Mueller tube on the axis of the spectrometer. Later, Keller, Koenigsberg and Paskin carried out numerical calculations
of the electron trajectories to find the ring focussing properties of a thin lens spectrometer. Figure 8 illustrates a portion of their results. From these calculations, they were able to improve the transmission of the instrument by a factor of two without an appreciable change in the resolving power. Pratt, Boley and Nicholls\textsuperscript{23} have since demonstrated, by photographic means, the existence of the ring focus.

The increased transmission of the modified spectrometer of Keller, Koenigsberg and Paskin was brought about by placing an annular baffle in the region of minimum separation between the electron trajectories. The electrons, after passing through this exit baffle, were detected on the axis. As can be seen from figure 8, the trajectories in the region of the detector may have a considerable spread and hence some of those electrons which pass through the annular baffle will not be detected. If a ring-shaped detector were to be placed at the region of minimum separation then an even greater increase in transmission could be achieved.

By using several coils concentric with the spectrometer axis, it is possible to reduce the effect of spherical aberration on the resolving power of a thin lens spectrometer. This type of spectrometer is known as a thick lens spectrometer\textsuperscript{24}. Thick lens spectrometers may or may not involve iron to shape their fields. The use of
an annular exit baffle increases the transmission of this type of instrument.

The various types of beta-ray spectrometers have been reviewed by Persico and Geoffrion. They have collected and tabulated the construction and performance data of a number of the instruments. The information in the following tables has been taken from more extensive tables in their paper.

Table 1. Data on some flat spectrometers

<table>
<thead>
<tr>
<th>Spectrometer Type</th>
<th>Iron Used Energy in Mev</th>
<th>Maximum Radius in cm</th>
<th>Resolving Path in cm</th>
<th>Transmission as %</th>
<th>Transmission in % solid angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single Focussing</td>
<td>Yes</td>
<td>3.1</td>
<td>12</td>
<td>1.6</td>
<td>0.10</td>
</tr>
<tr>
<td>Single Focussing</td>
<td>No</td>
<td>0.23</td>
<td>5</td>
<td>2.6</td>
<td>0.10</td>
</tr>
<tr>
<td>Double Focussing</td>
<td>(Yes)</td>
<td>5.6</td>
<td>12.5</td>
<td>0.27</td>
<td>0.134</td>
</tr>
<tr>
<td></td>
<td>(Yes)</td>
<td>6.0</td>
<td>17</td>
<td>0.35</td>
<td>0.32</td>
</tr>
</tbody>
</table>
Table 2  Data on some helical spectrometers.

<table>
<thead>
<tr>
<th>Spectrometer Type</th>
<th>Iron Used</th>
<th>Maximum Energy in Mev.</th>
<th>Distance between source and detector in cm.</th>
<th>Resolving Power as %</th>
<th>Transmission in % solid angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solenoidal with exit annular baffle (No) 4.44</td>
<td>90</td>
<td>2.5</td>
<td>2.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thin lens (No) 3.5</td>
<td>100</td>
<td>3.2</td>
<td>0.39</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thin lens with angular exit baffle (No) 3</td>
<td>114</td>
<td>1.5</td>
<td>0.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thick lens (Yes) 4</td>
<td>50</td>
<td>2.9</td>
<td>1.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thick lens with annular baffle Yes</td>
<td>-</td>
<td>4.0</td>
<td>8.0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
II

MODIFICATION OF A THIN LENS SPECTROMETER

A. PREVIOUS MODIFICATION:

The thin lens spectrometer is perhaps the most widely used type of spectrometer. It is capable of yielding measurements over a fairly wide energy range (100 Kev to 3 Mev generally) with reasonable resolving power (3%) and transmission (0.3%). Also, it is relatively inexpensive to build. As was mentioned earlier, the transmission of this type of spectrometer may be increased by making full use of its ring focussing property. Deutsch, Elliott and Evans suggested that the spherical aberration of a thin lens spectrometer might be reduced by the addition of small axial fields. Attempts to reduce the spherical aberration of a thin lens spectrometer by this means had previously been made in this laboratory by J. A. L. Thomson (unpublished).

A thin lens spectrometer of standard design was used in the work which is described below. The horizontal component of the magnetic field was compensated for by aligning the spectrometer tube with the horizontal component of the earth's magnetic field. The vertical component was annulled by the use of two large Helmholtz coils. The field magnet of this spectrometer consists of four water-cooled concentric coils. In the instrument used, the second
innermost coil was inoperative due to an accident during an earlier experiment. Any number of the remaining three coils could be connected together in series. Thomson's work was done using only the outer two coils in series.

Before attempts to improve the thin lens spectrometer characteristics could be made, the electron trajectories of the spectrometer were required. These were found experimentally by Thomson using two methods. First, a light current-carrying wire was used to simulate the trajectories, the tension in the wire corresponding to the momentum of the electrons. By this means it was hoped that the trajectories of the spectrometer could be obtained. This method proved to be unsatisfactory when it was found that in certain fields, the wire was dynamically unstable. A second method was then introduced, that of an electron gun and a lucite screen coated with zinc sulphide which scintillates under electron bombardment. The brass end-plate at the detector end of the spectrometer was replaced by a lucite plate to allow observation of the screen. The electron gun was mounted inside the spectrometer with provision made to vary the angle between the gun axis and the spectrometer axis. The zinc sulphide screen, upon which concentric circles had been drawn to facilitate measurements, was placed between the electron gun and the lucite end-plate. By varying the initial angle and the momentum of the electron beam for various positions of the zinc sulphide screen, Thomson was
able to obtain the trajectories of the spectrometer and to study the ring focussing properties of the spectrometer. Investigation of the focal lengths and aberrations of the modified spectrometer was made using an optical analogue. In this analogue, the main coil was considered as a thin lens and the additional axial coil as a very thin lens. Unfortunately, no record was kept of the results of these measurements.

The final arrangement decided upon by Thomson is shown in figure 9. The source and detector were no longer equidistant from the main coil but rather the source was now much nearer to the main coil than the detector. The detector was placed in the plane of the ring focus. A small coil, which acted as a dipole, was placed on the axis of the spectrometer, not directly below the main coil but closer to the detector.

It was mentioned above that Geiger-Mueller tubes replaced photographic plates as the means of electron detection in beta-ray spectrometers. Recently, scintillation crystals with photomultipliers have been replacing Geiger-Mueller tubes as the means of detecting the electrons. The detector built by Thomson is shown in figure 10. Scintillation crystals (anthracene) were "cemented" by a heavy silicone oil (Dow-Corning 200) into a ring at the base of a truncated, thin walled lucite cone. The
Figure 9  The Modified Spectrometer (with old detector)
top of the cone was butted against a short lucite rod. Between the cone and the rod was a pocket filled with Nujol mineral oil. The other end of the rod was optically coupled to a photomultiplier tube with a seal of the silicone oil. A groove was cut in the lucite rod to provide a means for a vacuum seal. The outside of the cone and rod assembly was heavily coated with magnesium oxide. This was done by holding the detector assembly in the smoke of burning magnesium. A thin coating of magnesium oxide was deposited on the surfaces of the crystals.

The detector was supported loosely on a spider arrangement since the main support and alignment was effected by the vacuum seal between the detector and the spectrometer end-plate. The detector is mounted in the spectrometer from the source end by pushing the spider arrangement down the tube until the groove cut in the lucite rod was past the end plate of the spectrometer. A split brass collar was then placed in the groove and the detector was pushed back into the spectrometer until the brass collar was flush with the end plate. A mixture of Apiezon Q and stop-cock grease was applied around this joint providing a vacuum seal.

A ring exit slit of aluminum was mounted approximately one cm. in front of the crystals of the detector. The width of the annulus was 5/32 inches. Between this
FIGURE 10 ORIGINAL DETECTOR

ALL CROSS SECTIONS CIRCULAR

Figure 10  Original Detector
exit baffle and magnet coils was another ring baffle of annular width 2.4 cm. The dipole element provided a center baffle against direct gamma radiations reaching the crystals.

The dipole element consisted of two parts: an inner coil and an outer coil. The space between these coils was to have been used for cooling water. The dipole was connected in series with the two main magnet coils, the leads being brought into the spectrometer chamber through two Kovar seals. A variable resistance was shunted across the dipole and was adjusted to give optimum current through the dipole.

The source was also mounted on a spider arrangement. A thin source of Eu, mounted on a backing of rubber hydro-bromide (700 mg/cm² thick), was used to obtain, empirically, the optimum operating conditions for this modification. The diameter of this source was approximately two mm.

The scintillation photons produced by the focussed electrons in the crystals were transmitted by the lucite "light-pipe" to the photomultiplier (RCA 5819). The photomultiplier was encased in a mu-metal cylinder and inside a cast iron cylinder to prevent magnetic interference. The output pulses were taken from the anode of the photomultiplier and fed into a pre-amplifier consisting of one stage of amplification (6AK5) and a cathode follower.
(paralleled 6J6). The cathode follower was matched into a 100 ohm coaxial cable which fed the pulses into a Linear Amplifier (Model 204-B; Atomic Instruments Co.). The output of the discriminator of the amplifier was fed into a Scale of 64 (Atomic Instruments Co.). Negative HT (between 600-700 volts) was applied across the photomultiplier from a standard, stabilized supply. The voltages for the pre-amplifier were obtained from another stabilized supply of standard design.

The current for the main magnet coils and for the axial dipole was controlled in the following manner. The current through the field producing elements also passed through a bank of 38 paralleled 6AS7-G's and through a standard resistance made of manganin strip. The voltage produced across the standard resistance was compared to that from a Rubicon potentiometer by means of D.C. and A.C. amplifier circuits. The output of these circuits was fed back to the grids of the 6AS7-G's in the correct phase to correct any difference between the compared voltages. The potentiometer was calibrated from time to time against a standard cell. By varying the voltage from the Rubicon potentiometer, the current in the main magnet coils and in the dipole could be changed and still be controlled. The current for the Helmholtz coils was obtained from the D.C. mains in the building and was stabilized by using two current regulator tubes (876) in series with the coils.
Using the equipment outlined above, Thomson claimed to have improved the resolving power by a factor of two and, at the same time, to have improved the transmission by a factor of four. However, when his equipment was used approximately a year later, we were unable to obtain these improvement factors and much of the previous work had to be repeated.

B. **SUBSEQUENT MODIFICATION:**

It was thought that if improvements could be made on the electronic equipment and on the optical coupling between the crystals and the photomultiplier, the efficiency of low energy electron detection might be increased. The conversion lines of Eu$^{152,154}$ were used to compare the present work with that of Thomson. These conversion lines have energies between 75 and 340 Kev.

The electronic counting equipment as used by Thomson was noisy and highly unstable. A number of changes were made. The available photomultiplier tubes were compared on another spectrometer using a conversion line of Se$^{75}$. A Dumont 6292 was selected as the best available photomultiplier. The literature on this type of photomultiplier suggests that since the characteristics of these tubes may vary from tube to tube, the voltage of the screen with respect to the photocathode should be adjusted to give the optimum characteristics. However, no appreciable change
in the gain of the tube was noticed when this voltage was varied between that of the photocathode and the first dynode. By using a tube socket of better grade bakelite and positive voltages on the photomultiplier considerable reduction in noise and some gain in stability were obtained. By changing the first stage of the Linear Amplifier from a pentode-connected to a triode-connected 6SJ7 a further reduction in noise was achieved. By dispensing with the one stage of gain in the pre-amplifier and using the cathode follower stage only, considerable gain in stability was obtained with a further reduction in noise. The arrangement of the components of the previous counting system was very susceptible to pick-up. By careful arrangement of grounds and of shielding, some of this susceptibility was reduced. With these changes in the electronic components considerable reduction in noise and very reasonable stability were achieved.

The optimum voltage to be applied to the photomultiplier was arrived at by comparing the measured intensities of two of the conversion lines of Eu$^{152,154}$, for various photomultiplier voltages, amplifier gains and discriminator settings. By this means, the most favorable voltage for the best low energy response was found to be 650 volts with the Linear Amplifier set at maximum gain. (The rise time was set at 0.2 μsec)

Low discriminator settings - and hence high
background counting rates - must be tolerated if all the significant counts, i.e. the counts over background, from the low energy electrons are to be counted. The dependence of the significant counting rate upon the discriminator setting is illustrated in figure 11. It should be noted that all the significant counts may be obtained with higher discriminator settings for higher energies. In practice this meant that the background could be decreased as the higher energy portions of the spectrum were examined.

The position of the source with respect to the main magnet coils was varied in an attempt to improve the transmission and resolving power. For each source position, various dipole currents were used. The transmission was greatest when the source was 20.6 cm. from the center of the main coils. The resolving power remained approximately the same for the various source positions. The best setting of the dipole shunting resistance was found to be that which allowed approximately \( \frac{1}{3} \) the main coil current through the dipole. (This corresponded to setting 4 on the variable resistance.) There was no noticeable increase in resolving power when the annulus of the exit baffle was decreased from 5/32" to 3/32".

The choice of scintillation crystals and the optical of coupling used were thought to have several disadvantages which, if overcome, would increase the efficiency
Figure 11: Effect of Discriminator on Significant Counts
of low energy electron detection and make the operation of the spectrometer easier. Since anthracene sublimes in a vacuum, the detector must be removed frequently to check the crystals and to replace those that have evaporated. The magnesium oxide coating on the detector brushed off very easily, making the removal and replacement of the detector a very tedious job. Two factors in the geometry of the lucite light-pipe (see figure 10) were thought to result in loss in light intensity between the scintillation crystals and the photomultiplier. First, the shallowness of the conical portion might result in many reflections being required by the light as it travelled from the crystals to the photomultiplier. Second, the groove cut in the cylindrical portion might prevent some of the light from reaching the photomultiplier.

Stilbene crystals, which are relatively stable in a vacuum, were substituted for the anthracene. However, since the light output from stilbene is approximately one-half that of anthracene, the efficiency of electron detection for low energies was very poor and that for higher energies only moderate. Consequently, anthracene crystals were re-installed.

The reflections from the magnesium oxide coating on the detector are diffuse reflections, and this can lead to an increased number of reflections between the crystals and the photomultiplier. It was decided to investigate
the operation of the detector with specular rather than diffuse reflections. The magnesium oxide was removed and the lucite was coated with aluminum, except for the ring in which the crystals sat and the end which coupled on to the photomultiplier. (The aluminizing apparatus is in another laboratory of this department.) Using anthracene crystals, the detector was mounted in the spectrometer and a test run made with the Eu source. The results indicated a very low response, particularly in the low energy region. This was interpreted as the result of poor optical coupling probably caused by high conduction losses in the aluminum layer. The magnesium oxide, therefore, provided a better reflecting surface than did the aluminum.

Accepting the oxide coating, an attempt was made to improve the geometry of the optical coupling. A new lucite light-pipe was designed (see figure 12). The following are the main conditions which influenced its design. If the conical section could be made deeper, the light leaving the crystals could reach the photomultiplier after fewer reflections. Also, since there is no loss of light from critical internal reflections, the surfaces of the detector should be shaped to make as many reflections as possible critical. By considering a point source of light and demanding that the light from this source be critically reflected from a surface, it can be shown that the equation of this surface is an exponential spiral. By a suitable
choice of the position of the point source, i.e. the zero of the co-ordinate axes, the point source may be replaced by a finite source and the critical reflection requirements will still be satisfied.

Two other factors were considered in the design of this detector. First, the apex of the inner conical surface should extend into the cylindrical section. This would prevent the light from one side of the conical section being reflected back into the other side. Second, the groove in the cylindrical section should be replaced by a shoulder (with the larger dimension on the photomultiplier side). This would prevent light from being trapped by the decrease in diameter at the groove.

Several limiting factors were also considered. First, the position of the crystals with respect to the main coils must remain the same as it was with the old detector. To obtain this condition it would be necessary to shift the spectrometer tube along the axis of the main coils. Second, the length of the cylindrical section and the shape of the conical section must allow adequate clearance between the detector and the end-plate of the spectrometer to enable the brass collar to be attached to the detector during mounting.

The lucite cone which evolved from these considerations is shown in figure 12. The spiral surfaces were based on an index of refraction of 1.6. A lucite
ALL CROSS SECTIONS CIRCULAR

FIGURE 12 MODIFIED DETECTOR
block 6"X6"X5" consisting of twelve ½ inch layers of lucite cemented together was obtained from a local firm (Plexolite Plastics Limited). This block was then machined to the specifications given in figure 12.

Anthracene crystals (approximately 1/32" thick) were cemented into the ring with the high viscosity silicone oil. The entire detector, excepting the crystal faces and the surface which is coupled to the photomultiplier, was heavily coated with magnesium oxide. The detector was mounted as before. The photomultiplier was coupled to the detector with the silicone oil.

This new detector, when tested, was found to increase the efficiency of low energy electron detection as determined by the conversion line spectrum of Eu$^{152,154}$. The increase in efficiency was estimated to be approximately a factor of 6½ over the previous detector.

Using only the outer two coils of the main magnet, the upper energy limit due to heating of the uncooled dipole was around 400 Kev. With the dipole disconnected the upper limit is determined by the capacity of the magnet cooling system. Tests indicate that this was approximately 740 Kev. This limitation greatly restricts the usefulness of this spectrometer for most beta-ray work. When the innermost coil was used as well as the two outer coils in an attempt to increase the maximum energy that can be measured it was found that the transmission and resolving power were not
appreciably changed from those obtained using two coils, and the maximum energy was increased to 1.5 Mev. Furthermore, using the three coils, the resolution and transmission were found to be almost entirely independent of the dipole current or polarity. This indicated that the field contribution of the dipole element does not greatly modify the main field produced by the three coils. In succeeding investigations the dipole was left in position but only as a baffle.

This modified spectrometer was compared with a conventional thin lens spectrometer by means of the lower energy portion (below 950 Kev) of the beta spectrum of $^{124}$Sb. Two different sources were used in this comparison, the one used in the modified spectrometer was 1/3 as intense as that used in the conventional spectrometer. The spectra obtained with these spectrometers are shown in figure 13. The resolving power as measured on the distinct conversion line was 2.2% for the conventional spectrometer and 2.3% for the modified spectrometer. The transmission of the modified spectrometer was found to be approximately 9 times as great as that of the conventional spectrometer in the energy region below 500 Kev and approximately 6 times as great in the higher energy region. The increase at low energies is attributed to better sensitivity of the detector for low energy electrons.

The value of the improvement brought about by the ring focus detection discussed above is best illustrated
Figure 143  Portion of Beta Spectrum of Sb$^{124}$

Spectrum obtained with modified spectrometer using source whose relative intensity was $\frac{1}{3}$ that used with conventional spectrometer.
by means of the following table. This table is based on Tables I and II. The fourth column contains a figure of merit, $M$, defined as the ratio of the resolving power to the transmission. The smaller this figure of merit, the better the spectrometer. We point out that this method of comparison does not take into consideration the physical size of the instrument, the maximum energy that may be examined, the size of the source nor the use of iron.

### TABLE III  Comparison of Spectrometer Data.

<table>
<thead>
<tr>
<th>Spectrometer type</th>
<th>Resolving Power</th>
<th>Transmission</th>
<th>$M$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>in %</td>
<td>in %</td>
<td></td>
</tr>
<tr>
<td><strong>W-type</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Single focussing</td>
<td>(1.6</td>
<td>0.10</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>(2.6</td>
<td>0.10</td>
<td>26</td>
</tr>
<tr>
<td>Double focussing</td>
<td>(0.27</td>
<td>0.134</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>(0.35</td>
<td>0.32</td>
<td>1</td>
</tr>
<tr>
<td><strong>Helical type</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Solenoidal with annular exit baffle</td>
<td>(2.5</td>
<td>2.0</td>
<td>1.2</td>
</tr>
<tr>
<td></td>
<td>(6.5</td>
<td>5.0</td>
<td>1.3</td>
</tr>
<tr>
<td>Thin lens</td>
<td>(3.2</td>
<td>0.39</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>(1.7</td>
<td>0.19</td>
<td>9</td>
</tr>
<tr>
<td>Thin lens with annular exit baffle</td>
<td>1.5</td>
<td>0.5</td>
<td>3</td>
</tr>
<tr>
<td>Thick lens</td>
<td>(2.9</td>
<td>1.0</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>(4.3</td>
<td>2.0</td>
<td>2</td>
</tr>
<tr>
<td>Thick lens with annular exit baffle</td>
<td>4</td>
<td>8</td>
<td>0.5</td>
</tr>
</tbody>
</table>
It can be seen from the values of $M$ in Table III that the best spectrometer characteristics are obtained with the thick lens spectrometer with annular exit baffle ($M = 0.5$). The next best of the helical spectrometers is the solenoidal spectrometer with annular exit baffle ($M = 1.2$). The unmodified thin lens spectrometers have $M$ values of 8 or 9.

With the modification reported here, the transmission of a thin lens spectrometer has been increased by a factor of at least 6. This increase in transmission would reduce the value of $M$ to, at the most, 1.5. The thin lens spectrometer is then comparable with the more expensive solenoidal spectrometers.

The results of this experiment indicate the need for closer examination of the possibilities of ring focus detection for different source and detector positions and for different emission angles. Such a search program is now in progress, using numerical methods of integration of the differential equation of the electron paths in the focusing field. It is felt that when these calculations have been completed, an entrance baffle may be designed which will further increase the resolving power of the instrument without any serious loss in the transmission. Or alternatively, a better source position or ring focus position may be found which will further improve the $M$ value of the spectrometer.
We think that this method of improving the characteristics of a thin lens spectrometer has excellent possibilities. Not only is it inexpensive, but it has several adjustable parameters such as source position and ring focus position. When applied to spectrometers with complete magnet coils (the second innermost coil of this spectrometer was inoperative) the regions of higher fields would also be regions of higher dispersion and this may result in higher resolving powers.
III

INVESTIGATION OF Eu$^{152,154}$

A. PREVIOUS INVESTIGATION

When the stable isotopes of Europium (47.8% Eu$^{151}$ and 52.2% Eu$^{153}$) are irradiated by slow neutrons, radioactive isotopes of atomic weights 152 and 154 are formed by (n,$\gamma$) processes. Lockett and Thomas$^{28}$ report that the long-lived activity of the mixture of these isotopes has a half-life of 12.4 years. Previously, Karraker, et al$^{29}$ had reported half-lives of 13 and 16 years for the 152 and 154 isotopes respectively, while Hayden, et al$^{30}$ had reported half-lives of 5.3 and 5.4 years for these isotopes. The 152 isotope also has a metastable state with a 9.2 hour half-life; which seems fairly well understood$^{31}$. Because of these almost equal lifetimes, it is difficult to assign the radiation components of the long-lived activity to the proper isotopes.

Many workers have examined the long-lived activity of Eu$^{152,154}$. Cork, Sheffler and Fowler$^{32}$ used a $\pi$ spectrometer with photographic detection and reported gamma-rays with energies of 122, 247, 286, 343, 408 and 1230 Kev. By absorption measurements, they set the upper limit of the gamma rays at 1230 Kev and the upper limit of the beta spectrum at 930 Kev.
Wiedenbeck and Chu using coincidence counting techniques and absorption measurements reported that the beta spectrum was complex, with at least two groups. The energies of these groups were 620 and 1000 Kev.

Cork, Sheffler and Fowler examined the Eu decay again and reported essentially the same gamma-ray energies as before. They reported two beta groups with energies of 751 and 1570 Kev.

Shull, using a double focussing spectrometer, reported internal conversion lines corresponding to transitions of 123, 247, 286, 344 and 412 Kev. From an examination of the photo-electric spectrum, he identified transitions of 442, 772, 959, 1082 and 1402 Kev. He also found two beta groups with energies of 751 and 1575 Kev and with relative intensities of 4.9 to 1.2 respectively.

Cork et al reported gamma-ray transitions with energies of 122, 123, 244, 336, 720, 778, 964, 1086 and 1116 Kev in the long-lived activity of Eu.

Slattery, Lu and Wiedenbeck have proposed a decay scheme for each of the two isotopes. These decay schemes are shown in figure 14. These decay schemes are based on measurements of the coincidences between and the relative intensity of the gamma and beta radiations. Thin lens spectrometers were used to measure beta-gamma coincidences and crystal summing techniques were used to measure gamma-gamma coincidences. They have also made use of the
Figure 14  DECAY SCHEME  
OF EU$^{152,154}$  (ENERGIES IN KEV)
results of others who used sources enriched with the 152 isotope and the results obtained by others from examination of the radiations from the 9.2 hour state of Eu$^{152}$.

B. CURRENT INVESTIGATION

The source used in the investigation described here was europium oxide and had been prepared approximately 18 months previously by other workers in this laboratory. Since this source had been irradiated at least 18 months prior to this investigation, the 9.2 hour state of Eu$^{152}$ had decayed away. The mounting of the source in the spectrometer has been described before. The source backing, rubber hydro-bromide, proved to be an insulator and this resulted in source charging. In spite of Aquadag paths being laid on the backing between the source and the aluminum holder, the source was found to charge up to roughly 1500 volts. No correction for this has been applied to the calculations which follow since the exact amount of source charging was unknown.

The modified thin lens spectrometer and the ancillary equipment which has been described above was used in obtaining the beta and internal conversion spectra of the mixture Eu$^{152,154}$. These spectra are shown in figure 15.

The spectrometer was calibrated on the assumption
Figure 15. Measured Beta Spectrum of Eu$^{152,154}$

$\sqrt{\frac{N}{Z}} \times 100 < 1.4\%$ for all experimental points

Not all experimental points shown

Note change of scale

Sum of beta groups shown in Fig. 17

$N$ in units of m/cc
that the peak of the lowest energy internal conversion line corresponded to K-conversion electrons from the 122 Kev transition in Sm\(^{37}\). The conversion line energies which were obtained using this calibration and the corresponding transition energies, assuming that the electrons originate in either the Sm or the Gd nucleus, are given in Table IV.

**TABLE IV**

<table>
<thead>
<tr>
<th>ELECTRON ENERGY IN KEV</th>
<th>TRANSITION ENERGY IN KEV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sm</td>
</tr>
<tr>
<td>74.6 ± 0.7</td>
<td>121.5 ± 0.7</td>
</tr>
<tr>
<td>115.5 ± 1.2</td>
<td>123.3 ± 1.2</td>
</tr>
<tr>
<td>198.3 ± 2.0</td>
<td>245.2 ± 2.0</td>
</tr>
<tr>
<td>242.7 ± 3.0</td>
<td>250.5 ± 3.0</td>
</tr>
<tr>
<td>295.9 ± 3.0</td>
<td>342.8 ± 3.0</td>
</tr>
<tr>
<td>339.8 ± 3.4</td>
<td>347.6 ± 3.4</td>
</tr>
</tbody>
</table>

The shape of the high energy edge of the peaks corresponding to the 75 and 115 Kev electrons indicates that these peaks are each composed of two groups of internal conversion electrons. This is in agreement with previous measurements of 122 and 123 Kev transitions\(^{37}\). There is a faint indication of an electron line superimposed on the high energy side of the 340 Kev conversion line. This might correspond to the K conversion in Gd of the 410 Kev
transition reported by Slattery et al. 37.

The conversion lines, which are tabulated in Table IV, have been assigned to the following transitions. The 75 and 115 Kev lines have been assigned to a 122 Kev transition in Sm and to a 124 Kev transition in Gd. The 198 and 243 Kev lines have been assigned to a 245 Kev transition in Sm. The 296 and 340 Kev lines have been assigned to a 346 Kev transition in Gd. These assignments follow those of Slattery et al. 37.

The K-to-L ratios of the conversion lines corresponding to the 245 and 346 Kev transitions have been measured. They were found to be 2 and 4 respectively. The graphs of Goldhaber and Sunyar 7 indicate that the 245 Kev transition would have a spin change of 3 and a change in parity (this is written as E3, YES) or a spin change of 4 also with a change in parity (this is written as M4, YES) and that the 346 Kev transition would have a spin change of 2 with no parity change (this is written as E2, NO). No attempt was made to measure the K-to-L ratio of the 122-123 Kev transitions since this would presuppose that the spin and parity changes of the two transitions were the same.

A Fermi plot of the beta spectrum of Eu 152, 154 was made and a portion of it is shown in figure 16. Beta groups with end points of 1450±15, 1060±35 and 675±40 Kev were found by this method of analysis with the assumption that each transition is "allowed".
Figure 16 Portion of Fermi Plot for Energies Greater Than 360 keV (Eu$^{152,154}$)

End points: E = 3.84, E = 1450 keV
1.07, 1060 keV
2.32, 675 keV

(values of f = n^2F were taken from ref. 2)
The 1450 and 675 Kev beta groups are in agreement with those found by Slattery, Lu and Wiedenbeck\textsuperscript{37}. The 1060 Kev group has not been reported in the more recent papers on the decay of Eu\textsuperscript{152,154}. Two of the earlier papers\textsuperscript{32,33} do report beta groups of 930 and 1000 Kev but only on the basis of absorption measurements which are not too accurate. From energy considerations only, the 1060 Kev group could correspond to a beta transition between the ground state of Eu\textsuperscript{152} and the ground state of Gd\textsuperscript{152} (see figure 14).

The Fermi plot of the beta spectrum was not made for energies less than 360 Kev for two reasons. First, the density of the conversion line spectrum in that region masks the low energy beta distribution. Second, the errors which accumulate after three subtractions make any further subtractions of dubious value.

The individual beta distributions have been calculated from the separation effected by the Fermi plot. They are shown in figure 17. The relative intensities of the three beta groups have been measured from these distributions and are given in Table V.

<table>
<thead>
<tr>
<th>\beta GROUP</th>
<th>RELATIVE INTENSITY</th>
</tr>
</thead>
<tbody>
<tr>
<td>1450 Kev</td>
<td>2.0</td>
</tr>
<tr>
<td>1060 Kev</td>
<td>2.6</td>
</tr>
<tr>
<td>675 Kev</td>
<td>9.7</td>
</tr>
</tbody>
</table>
Figure 17  Beta Groups of Eu$^{152,154}$

Relative Intensities
675 $\beta$ Group 9651
1060 $\beta$ Group 2626
1450 $\beta$ Group 2030

Vertical Scale
Halved for this $\beta$-Group
The relative intensity of the 1575 and the 751 Kev beta groups as determined by Shull\textsuperscript{35} were 1.2 and 4.9.

The individual beta distributions have been added together and the sum is shown in figure 15 (shown by the x's) along with the measured beta spectrum. The difference between these two spectra is some indication of the presence of another beta group whose energy would be approximately 330 Kev. This is in agreement with the results of Slattery, et al\textsuperscript{37}.

Estimates of the comparative lifetimes of the 1450, 1060 and 675 Kev beta transitions have been made using the nomographs of Moszkowski\textsuperscript{5}. Each beta group was found to have a log $\tau$ value of approximately 11. These rather large values of the comparative lifetimes indicates that the transitions are second (or higher) forbidden. If these transitions are second (or higher) forbidden then the beta energies that were found by straight line Fermi plots would be in error, particularly the 1060 and 675 Kev transitions. In addition, the relative intensities quoted for these groups would probably be in error.

The K-to-L ratio of the conversion lines corresponding to the 346 Kev transitions indicated that this was an E2, NO transition. The proposed decay scheme (figure 14) places this transition between the first excited state and the ground state of the even-even nucleus, Gd\textsuperscript{152}. In
accordance with accepted empirical assignments, the spin of the Gd$^{152}$ ground state is zero and the parity is even (written as $0^+$). Therefore, the 346 Kev transition must then come from a state whose spin is $2^+$. If the 1060 Kev beta transition between Eu$^{152}$ and Gd$^{152}$ ground states is forbidden, as well as the 675 Kev beta group, this would indicate that the spin of the Eu$^{152}$ ground state is rather large. Some indication that this is so may be had by looking at the shell model predictions for odd Z, odd N (the number of neutrons) nuclei, such as Eu$^{152}$.

The empirical rules of Mayer, Moszkowski and Nordheim state that the total spin of odd-odd nuclei is made up of the vector sum of the spins of the odd proton and odd neutron in the following way.

"If the odd proton and odd neutron are of the same Schmidt group (parallel or anti-parallel orbital and intrinsic spin vectors) the resultant spin is larger than the scalar difference of the individual spins and in some cases may be equal to the sum of the individual spins. If the odd proton and odd neutron are of different Schmidt groups the resultant spin is the scalar difference between the individual spins."

The Eu$^{152}$ nucleus consists of 63 protons and 89 neutrons. The shell model predicts that the odd proton
would be in a $d_{5/2}$ state (parallel Schmidt group) and the odd neutron in a $f_{7/2}$ state (parallel Schmidt group) or a $h_{9/2}$ state (anti-parallel Schmidt group). If the ground state of the nucleus consisted of the $d_{5/2}$ proton and the $f_{7/2}$ neutron, then the resultant spin would be at least 2 and at the most, 6. If the ground state consisted of the $d_{5/2}$ proton and the $h_{9/2}$ neutron, then the resultant spin would be 2. In either case, the parity of the Eu$^{152}$ ground state would be odd.

These considerations indicate that the Eu$^{152}$ ground state has a spin of 2 or greater and has opposite parity to that of the ground state and of the first excited state of Gd$^{152}$. This difference in parity means forbidden beta transitions since any parity change takes beta transitions out of the allowed class.

It is possible to consider the first excited state of Gd$^{152}$ as belonging to the "rotational" excitation levels of even-even nuclei predicted recently by Bohr and Mottelson$^{39}$. All such states have energies given by

$$E = \frac{\hbar}{2J}(I(I+1))$$

where $J$ = effective moment of inertia of the nucleus. The energy difference between adjacent levels is then given by $E = \frac{\hbar}{2J}(I-1)$ where $I$ is the spin of the higher level. According to the theory, all such states have even parity. On this basis, the next rotational level ($I = 4^+$) of Gd 152 should lie 807 Kev above the 346 level. If this were so, then we see that such a level would not
be excited in this decay. (It would lie above the ground state of Eu$^{152}$)

The predictions of the shell model as to the spin and parity changes involved in the decay of Eu$^{152}$ are not in disagreement with the values found experimentally. However, there is not enough information available at this time to make any sound conclusions as to the spin and parity changes involved.

Previous workers apparently have not investigated the possibility that the beta transitions may be forbidden and that the beta energies as determined by straight line Fermi plots may be in error. The results of the investigation reported here indicate that these transitions are at least second forbidden. The position in the Eu$^{152,154}$ decay schemes of several of the transitions (the 410 and 778 Kev gamma-rays and the associated beta-rays - shown by dashed lines) are doubtful even without considering that the beta groups are forbidden. If after further investigations these transitions are found to be forbidden then the proposed decay scheme of Slattery, Lu and Wiedenbeck will necessarily require modification.
REFERENCES


