1960

Decay Scheme of Cesium-134.

Parma Nand Trehan
Louisiana State University and Agricultural & Mechanical College

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DECAY SCHEME OF Cs$^{134}$

A Dissertation

Submitted to the Graduate Faculty of the Louisiana State University and Agricultural and Mechanical College in partial fulfillment of the requirements for the degree of Doctor of Philosophy in the Department of Physics

by
Parma Nand Trehan
B.S.(Honours) Panjab University, 1950
M.S.(Honours) Panjab University, 1951
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# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Acknowledgement</th>
<th>ii</th>
</tr>
</thead>
<tbody>
<tr>
<td>List of Tables</td>
<td>iv</td>
</tr>
<tr>
<td>List of Figures</td>
<td>v</td>
</tr>
<tr>
<td>Abstract</td>
<td>vii</td>
</tr>
<tr>
<td>Chapter</td>
<td></td>
</tr>
<tr>
<td>I. Introduction</td>
<td>1</td>
</tr>
<tr>
<td>II. Principle of Detection and Instrumentation</td>
<td>10</td>
</tr>
<tr>
<td>III. Measurements and Analysis</td>
<td>25</td>
</tr>
<tr>
<td>IV. Discussion of Decay Scheme</td>
<td>70</td>
</tr>
<tr>
<td>Bibliography</td>
<td>77</td>
</tr>
<tr>
<td>Vita</td>
<td>80</td>
</tr>
</tbody>
</table>
LIST OF TABLES

<table>
<thead>
<tr>
<th>Tables</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>I. Summary of the Experimental Data for the Relative Intensity of the</td>
<td></td>
</tr>
<tr>
<td>Various Gamma Rays of Cs$^{134}$</td>
<td>30</td>
</tr>
<tr>
<td>II. Possible Combinations Giving High Energy Sum Peaks</td>
<td>34</td>
</tr>
<tr>
<td>III. Summary of the Coincidence Data</td>
<td>44</td>
</tr>
<tr>
<td>IV. Energy and Intensity of the Various Beta Groups</td>
<td>51</td>
</tr>
<tr>
<td>V. K-Conversion Coefficients and K/(L + M) Ratio for Cs$^{134}$</td>
<td>61</td>
</tr>
<tr>
<td>Figures</td>
<td>Description</td>
</tr>
<tr>
<td>---------</td>
<td>-------------</td>
</tr>
<tr>
<td>Fig. 1.</td>
<td>Decay Scheme of Cs$^{134}$ as Accepted by Nuclear Data Cards.</td>
</tr>
<tr>
<td>Fig. 2.</td>
<td>High Voltage Power Supply Circuit for Fourteen Stage Photomultipliers</td>
</tr>
<tr>
<td>Fig. 3.</td>
<td>Block Diagram of &quot;Fast-Slow&quot; Coincidence Circuit</td>
</tr>
<tr>
<td>Fig. 4.</td>
<td>The Experimental Arrangement of the &quot;Coincidence Sum Spectrometer</td>
</tr>
<tr>
<td>Fig. 5.</td>
<td>Momentum Calibration Curve for Magnetic Spectrometer</td>
</tr>
<tr>
<td>Fig. 6.</td>
<td>Fermi-Kurie Plot for Cs$^{137}$. Upper Curve is a Normal Plot Whereas the Lower is Obtained After Shape Factor Correction</td>
</tr>
<tr>
<td>Fig. 7.</td>
<td>Gamma Ray Spectrum in the Decay of Cs$^{134}$ (Source Distance 40 cms.)</td>
</tr>
<tr>
<td>Fig. 8.</td>
<td>Gamma Ray Spectrum in the Decay of Cs$^{137}$. Dotted Curve Shows the Data After Back Scattering Correction</td>
</tr>
<tr>
<td>Fig. 9.</td>
<td>Gamma Ray Spectra for the Decay of Cs$^{134}$ at Different Distances.</td>
</tr>
<tr>
<td>Fig. 10.</td>
<td>High Energy Part of the Gamma Ray Spectrum of Fig. 9 After Careful Analysis (Source Distance 3.6 cms.)</td>
</tr>
<tr>
<td>Fig. 11.</td>
<td>Gamma Ray Spectra in Coincidence with 605 Kev Gamma Ray</td>
</tr>
<tr>
<td>Fig. 12.</td>
<td>Gamma Ray Spectra in Coincidence with 800 Kev Gamma Ray</td>
</tr>
<tr>
<td>Fig. 13.</td>
<td>Gamma Ray Spectra in Coincidence with 1038 Kev Gamma Ray</td>
</tr>
<tr>
<td>Fig. 14.</td>
<td>Gamma Ray Spectra in Coincidence with 1168 Kev Gamma Ray</td>
</tr>
<tr>
<td>Fig. 15.</td>
<td>Gamma Ray Spectra in Coincidence with 1367 Kev Gamma Ray</td>
</tr>
</tbody>
</table>
Figures

Fig. 16. Beta Ray Spectra in Coincidence with 605 Kev Gamma Ray. ........................................ 45
Fig. 17. Beta Ray Spectra in Coincidence with 800 Kev Gamma Ray. ........................................ 46
Fig. 18. Fermi-Kurie Plot of Cs$^{134}$ (High Energy Region). The Data on Analysis Shows Three Beta Groups of End Point Energies 1453, 892, and 655 Kev ............................... 48
Fig. 19. Fermi-Kurie Plot of Cs$^{134}$ (Low Energy Region). This Curve Shows Two Slopes Which on Analysis Give a Beta Group of 410 Kev as its End Point Energy .................................. 49
Fig. 20. Conversion Spectra for the Decay of Cs$^{134}$ (Low Energy Region) ........................................ 52
Fig. 21. Conversion Spectra for the Decay of Cs$^{134}$ (High Energy Region) ................................. 53
Fig. 22. Conversion Spectra for the Decay of Cs$^{137}$ (Source No.1) ........................................ 54
Fig. 23. Conversion Spectra for the Decay of Cs$^{134}$ (Source No.2) ........................................ 55
Fig. 24. Conversion Spectra for the Decay of Cs$^{137}$ (Source No.2) ........................................ 56
Fig. 25. Gamma Ray Spectra for the Decay of Cs$^{134}$ (Source No.2) ........................................ 57
Fig. 26. Gamma Ray Spectra for the Decay of Cs$^{137}$ (Source No.2) ........................................ 58
Fig. 27. Coincidence Sum Spectra with the Single Channel Analyzer Set at 1970 Kev. ................ 62
Fig. 28. Coincidence Sum Spectra with the Single Channel Analyzer Set at 1770 Kev. ................. 64
Fig. 29. Coincidence Sum Spectra with the Single Channel Analyzer Set at 1640 Kev. ................ 65
Fig. 30. Coincidence Sum Spectra with the Single Channel Set at 1401 Kev. ................................. 66
Fig. 31. Delay Curve of 800-605 Kev Gamma Rays ................................................................. 68
Fig. 32. Delay Curve of 1367-605 Kev Gamma Rays ................................................................. 69
Fig. 33. Decay Scheme of Cs$^{134}$ From the Present Work. The Energy, the Intensities and the Log ft Values of the Various Beta Groups are Shown ........................................ 71
The decay of $^{134}\text{Cs}$ and the energy level scheme of $^{134}\text{Ba}$ have been investigated using a scintillation spectrometer, a coincidence sum spectrometer, a magnetic spectrometer (double focusing type) and a coincidence scintillation spectrometer. From the analysis of the magnetic spectrometer data, the gamma ray scintillation spectra and the gamma-gamma coincidence data, the energy (in Kev) and the relative intensity of the gamma rays were found as $\sim 475 (1.2), 563 (9), 569 (13), 605 (100), 800 (92), 1038 (1.1), 1168 (0.6), 1168 (2.1)$, and $1367 (3.6)$. Single spectra analysis (with the source close to the crystal) showed sum peaks at 1168, 1401, 1643, 1770, and 1970 Kev thus establishing the presence of these levels in $^{134}\text{Ba}$. The levels at 1643, 1773, and 1970 Kev were confirmed by coincidence sum spectrometer data.

The beta ray spectra obtained with the magnetic spectrometer were analyzed using a Fortran program written for IBM-650. This analysis in conjunction with gamma-gamma coincidences resulted in five beta groups of energy (in Kev) and intensity as follows: $1453 (0.13\%), 892 (0.7\%), 655 (71\%), 410 (2.1\%), 86 (26\%)$. K-conversion coefficients of the gamma rays were measured using the 'comparison method' and multipolarities assigned. The assignments made to 563 and 1168 (of 2.1 relative intensity) Kev gamma rays were found to confirm those expected.
from the collective model. A gamma ray of energy 200 Kev and intensity 
(1 \pm 0.5)\% was observed in the magnetic spectrometer data.

A decay scheme of Cs$^{134}$ consistent with the various measurements 
is proposed. The spin and parity assignment to the various levels is 
made using the log ft values of the various beta groups and the 
measured K-conversion coefficients. The energy (in Kev), spin and the 
parity assignments of the various levels are: ground state (0$^+$), 
605(2$^+$), 1168(2$^+$), 1402(4$^+$), 1643(2$^+$), 1773(2$^-$ or 3$^-$) and 1970(4$^+$).
CHAPTER I
INTRODUCTION

The knowledge of the level scheme of a nucleus furnishes an important clue to its structure. By level scheme, we mean not only the energies of the levels but also their character: i.e., the spin and parity of each level and the transition probabilities for the decay of excited states. During the last few years, a great amount of experimentation has been done in this field by studying radio-active decay, inelastic scattering of charged particles and neutrons and the production of gamma rays resulting from neutron capture. The results of such experiments show some regularities which can be at least partially understood in terms of the theory of collective model discussed below.

It is quite evident in those nuclei which have an even number of both protons and neutrons (even-even nuclei) that they possess the following regularities:

1. The ground state is $0^+$ without any known exception. The first excited state is $2^+$ with very few exceptions.$^{1,2}$

---


(2) The energy of the first excited state is correlated with the proton and the neutron number, and it passes through distinct maxima at closed shells.

These nuclei, having neutron number either between 90 and $\sim 112$ or above $\sim 134$, are found to obey the collective model of Bohr and Mottelson. The even-even nuclei in these regions are characterized by a rotational band of the ground state with characters $0^+, 2^+, 4^+\ldots$, where the energy of the state with spin $I$ is proportional to $I(I + 1)$.

In the region between 36 and 88 neutrons ($66 \leq N \leq 150$) Scharff-Goldhaber and Weneser have found surprising regularities in the even-even nuclei, different from those of the rotational region, which are given below:

1. The ratio of the energy of the second excited state ($E_2$) to that of the first ranges between 2 and 2.5. Only in cases where the proton or neutron number is near to the closed shell, we find $E_2/E_1 < 2$.

2. The second excited state is either $0^+$, $2^+$, or $4^+$, but preponderantly it is found to be $2^+$.

3. If the second excited state is $2^+$, there are certain rules for the transition probabilities and for the multipole orders of the transitions which were first pointed out by Kraushaar and

---


Goldhaber.\textsuperscript{5}

(a) The transition from the second to the first $2^+$ state is usually E2 with only a small mixture of M1, whereas the shell model would predict that the M1 transition should be about 500 times stronger than the E2 transition.

(b) The ratio of the crossover transition (second excited state to the ground state) to that of the cascade transition (second excited state to the first excited state) is usually found to be less than 1 whereas the shell model predicts it to be 25.

All these features suggest a collective behavior of these nuclei. Scharff-Goldhaber and Wenser\textsuperscript{4} explained these results by using the Bohr-Mottelson model in the region of weak to moderate coupling\textsuperscript{3} and extending it to include the interaction between an even number of particles outside the closed core. They consider the case when the nucleus is freely vibrating in a collective motion: i.e., it involves no coupling with individual nucleon motions. Such a freely vibrating body will have harmonic vibrational states for small amplitudes; the first excited state would correspond to an energy of one phonon $\hbar\omega$, and the second excited state would have two phonons as the excitation energy. The second excited state would be a degenerate triplet with characters $0^+$, $2^+$, and $4^+$. The ratio of the second to the first excited state $E_2/E_1 = 2\hbar\omega/\hbar\omega = 2$ explains the minimum value as found experimentally. In such a case M1

\textsuperscript{5}J. J. Kraushaar and M. Goldhaber, Phys. Rev. 89, 1081 (1953).
transitions would be completely forbidden since the vibrations are axial, and only pure E2 transitions from the second to the first excited state would occur. This explains the first intensity rule 3(a). The second intensity rule 3(b) follows from the fact that one phonon jump is favored over that of two, causing only a very weak transition from the second $2^+$ state to the ground state. By considering the coupling of individual nucleons to the core (having closed shell) with free phonon (surface) vibration, they introduce a small admixture of M1 transition and also increase the energy ratio of the second to the first $2^+$ excited state. Also this additional coupling term gives the order of the degenerate triplet of the second excited state as $4^+$, $2^+$, and $0^+$. The sequence of these levels is not very rigid and can be changed by introducing an anharmonic term. A very good example of this is found in case of Cd$^{114}$ where the sequence of levels has been found experimentally as $2^+$, $4^+$, and $0^+$ instead of $4^+$, $2^+$, and $0^+$.6

Wilets and Jeans7 have given another explanation of the vibrational behavior of even-even nuclei. Their model assumes collective surface oscillations where the individual nucleons are treated in first approximation as only contributing to an effective potential energy through their coupling to the surface (strong-coupling approximations). The predictions of their model are found to agree with that proposed by Scharff-Goldhaber and Weneser.

7L. Wilets and M. Jean, Phys. Rev. 102, 788 (1956).
To study the applicability of these models to the even-even nuclei, an extensive investigation of $^{56}\text{Ba}^{134}$ level scheme was undertaken. A brief summary of the various investigations so far conducted on this nucleus is given below:

The decay of 2.19 year Cs$^{134}$ which leads to excited levels of Ba$^{134}$ by beta emission has been extensively studied by several groups using various aspects of beta and gamma ray spectroscopy. However, its decay scheme is still incompletely known because of the complexity of its beta and gamma ray spectra. From magnetic spectrometer measurements made by Waggoner, Moon, and Robert, Joshi and Theosar, Bertoline, Bettoni, and Lazzarini, Cork et al., Keister, Lee and Schmidt, eleven gamma rays have been reported with average energies of 202, 475, 563, 569, 605, 797, 802, 1038, 1168, 1367, and 1401 Kev. Two gamma rays have been reported by Girgis having energies 960 and 1570 Kev from single

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8 Nuclear Data Sheets, National Research Council, Washington, D.C.
and sum spectra studies. Two more gamma rays having energies 1640 and 1970 Kev have been reported by French and Goodrich, but these were later attributed to the sum pulses. The gamma rays having energies 960, 1401, and 1570 Kev have been observed only once and seem to be doubtful. The 202 Kev gamma ray has been reported twice, and the rest have been reported three or more times.

Nine beta groups have been detected. Of these the 86 and the 655 Kev beta groups are well established, and the rest are doubtful because of the disagreement amongst the various workers.

The internal and external conversion coefficients of the various gamma rays have been measured by different groups. The most extensive conversion coefficient measurements were done by Keister, Lee and Schmidt. Multipolarities were assigned to the various gamma rays by these authors. The internal conversion coefficient measurements on the high energy gamma rays were repeated by Friel and Weber. No group has yet been able to assign definite multipolarities to some of these gamma rays.

The first decay scheme of Cs was put forward by Bell and Elliot. Since then a good deal of information has been collected. The latest decay scheme incorporating the most acceptable data has

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18 L. G. Elliot and R. E. Bell, Phys. Rev. 72, 969 (1947).
appeared in Nuclear Data Cards\(^8\) while the present investigations were conducted. It is shown in Fig. 1.

From the study of the results reported by the various groups\(^8\) it is quite evident that there is a great disagreement about the existence and the position of certain beta-groups and gamma rays in the decay scheme. Also the characteristics of some levels are uncertain. These disagreements led us to investigate the decay scheme of Cs\(^{134}\) nucleus. A thorough investigation of the internal conversion coefficients of the various gamma rays along with a careful analysis of the beta-ray spectra was proposed. A double focusing magnetic spectrometer after the design of Swartholm and Siegbahn\(^{19,20}\) was used for this purpose. It was hoped that definite spin and parity assignments could be made on the basis of these measurements. A complete analysis of the single and sum spectra due to gamma rays was also undertaken. It was expected that this analysis could enable us to determine the relative gamma ray intensities and their positions in the decay scheme. A further study of the sum pulse spectrum was made with a coincidence sum spectrometer constructed after the design of Hoogenboom.\(^{21}\) This would enable a confirmation of the position of the various high energy levels in the decay scheme. A careful re-analysis of the coincidence data obtained by French\(^{22}\) was

\(^{21}\)A. M. Hoogenboom, Nuclear Instruments, 3, 56 (1958).
\(^{22}\)John D. French, Ph.D. Dissertation submitted to the Louisiana State University (1958).
Fig. 1. Decay Scheme of $\text{Cs}^{134}$ as Accepted by Nuclear Data Cards.
done with the hope of removing certain discrepancies. A 'fast-slow' coincidence circuit was constructed after the design of Bell\textsuperscript{23} in order to make measurements of the life times (of certain levels) of the order of $10^{-10}$ sec.

\textsuperscript{23}R. E. Bell, R. L. Graham, and H. E. Petch, Canad. J. Phys. 30, No. 1, 35
CHAPTER II
PRINCIPLE OF DETECTION AND INSTRUMENTATION

The techniques of detecting and measuring nuclear radiations have been developed extensively during the last few years, mainly due to the advent of scintillation counters. The principle of detection of these counters can be outlined briefly as follows. A gamma ray or a charged particle falling on the scintillating crystal, knocks out electrons from an atom of the crystal and imparts it some kinetic energy which is related in amount to the energy of the incident particle. This electron then moves inside the crystal until it loses all its energy through excitation or ionization of other atoms of the crystal (NaI or plastic phosphor in these experiments). The light output from the various parts of the crystal as a result of de-excitation travels through it and impinges on the photo-cathode surface of the photo-tube. This results in the liberation of the photo-electrons from the cathode. These electrons are multiplied in several stages of the photomultiplier and finally collected on its anode. An output pulse from the anode is then fed to the preamplifier which has a cathode follower output stage going to the linear amplifier. The height of the output pulses of the linear amplifier is then analyzed by a single channel or a multichannel analyzer.
In the present investigation of Cs^{134} the following instruments were used:

(1) A scintillation spectrometer using a 3 inch x 3 inch cylindrical NaI(Tl) crystal mounted on a Dumont type 6363 photomultiplier tube.

(2) A fast-slow coincidence scintillation spectrometer using two 1 inch x 1\frac{1}{2} inch diameter NaI(Tl) mounted on two RCA 6810-A photomultipliers with a fast-slow coincidence circuit.

(3) A coincidence spectrometer using two 3 inch x 3 inch crystals with 6363 Dumont tubes.

(4) A double focusing magnetic spectrometer.

A brief description of the various units involved follows:

(A) Crystal and Photomultiplier Assembly

The crystal mounting on the photomultiplier tube is of extreme importance as the resolution of the crystal is considerably affected if the mounting is not proper. Since the NaI(Tl) crystal is hygroscopic, it has to be packed carefully in a dry box.

A pair of 3 inch x 3 inch crystals were used for the coincidence sum spectrometer out of which one crystal was also utilized for singles spectrometer. They were packed in the laboratory according to the method described by Bell.\(^{24}\)

Another pair of photomultipliers type RCA 6810-A were used for the "fast-slow" coincidence circuit. The 1\frac{1}{2} inch x 1 inch cylindrical crystals employed with these tubes were packed hermetically by the Harshaw.

Fig. 2. High Voltage Power Supply Circuit for Fourteen Stage Photomultipliers.
Chemical Co. These crystals were mounted on the photomultiplier tubes using silica gel and were covered with black Scotch tape to make the tubes light tight. The resolution of the various crystals mounted varied from 9 to 10.5% for the 661.6 KeV gamma ray of Cs$^{137}$.

(B) **Power Supply**

A regulated power supply of conventional design has been used for the Dumont 6363 photomultiplier tubes. The voltage generally applied to the photo-tube was about 800 volts. This voltage was constantly monitored by a potentiometer and was found to stay stable to better than ± 0.2 volts.

A heavy duty negative voltage power supply was required for the RCA 6810-A photomultipliers. These photomultipliers are fourteen stage type and require special power supplies capable of delivering 12 ma of current at 2000 volts. Such a power supply was designed and constructed in the laboratory. The circuit for this power supply is shown in Fig. 2. A string of 5651 voltage regulator tubes was used in the circuit (as shown) in order to improve the stability of the circuit. This power supply could be varied in voltage output from 1800 to 2300 volts. It showed a stability better than 0.2 volts when used in conjunction with a sola constant voltage transformer.

(C) **Preamplifier, Linear Amplifier, and Single Channel Analyzer**

The circuit for one of the preamplifiers was after the design of Jordan and Bell$^{25}$ and the preamplifier has a gain of 10. The preamplifier and the twenty channel analyzer with which it was used were (Model 521)

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supplied by Atomic Instrument Co. The preamplifier has a gain of 30. Both preamplifiers could handle pulses with a rise time as fast as 0.25 μsec.

The wide band amplifiers were built by Atomic Instrument Co. Each include a pulse height selector unit which gives a fixed output. Two different outputs could be obtained, one directly from the linear amplifier which is proportional to the input, and the second from the pulse height selector unit which has a fixed output.

The output of the linear amplifier is then fed to the single channel analyzer or the twenty channel analyzer. The former has been built in the laboratory after the design of Francis and Bell. The output of the single channel analyzer is recorded by a binary scaler.

(D) "Fast-Slow" Coincidence Circuit

This circuit was constructed for the measurement of life time of various states and for coincidence studies. The block diagram of the electronic circuit is shown in Fig. 3. It incorporates a fast coincidence circuit whose resolving time can be varied from 4 n-sec onwards. The type of photomultiplier tubes used were RCA 6810-A having an intrinsic pulse spread of only 1 n-sec. The voltage outputs from both the photo-tubes are taken at two places, one at the anode and the other at the seventh dynode. The dynode outputs are fed to two preamplifiers 'A'. The output from one of the preamplifiers is taken to

a 204-B Atomics Linear amplifier, single channel analyzer, a pulse shaper and then fed to the slow coincidence circuit as one of the input.

The outputs from the anodes of the 6810-A photomultiplier tubes give negative pulses of about 100 volts for 800 Kev gamma rays. These outputs are directly fed to the fast coincidence circuit consisting of pulse limiters and a diode mixer designed on the basis of one given by Bell et al. The limiter circuit for each photo-tube was built under the chassis on which the photo-tube itself was mounted. The mixed output of the two limiter circuits is fed to a 1N21 coincidence diode which has been suitably biased (for detailed discussion see Ref. 27). The output from the coincidence diode is of the order of only a few milli-volts and is a function of the bias setting of the diode. This output pulse is fed to model 204-B linear amplifier (Atomic Instrument Co.). No cathode follower was needed since the crystal diode was mounted on the linear amplifier itself. Due to the non-linear characteristics of the crystal diode, it could be used to discriminate between coincidence and single pulses. The coincidence to single output pulse ratio was obtained as 5-8:1 with suitable adjustment of 10 Kilo-ohm helipot. The diode output is fed to the linear amplifier whose gain was set to get an output pulse of 20-30 volts. The singles output pulses were further discriminated against by using a single channel differential analyzer as an integrator. It was observed that the resolving time of

the coincidence circuit depended upon the length of 50 ohms shorted cable (as expected) and the setting of the integral discriminator. The coincidence resolving time can be measured by introducing positive or negative delay on one side and then plotting a graph of delay vs. output counting rate. The width at half maximum gives the resolving time. The output of the fast coincidence circuit is fed as the second input to the slow coincidence circuit which had a resolving time of about \(1 \mu \text{sec}\). The output of the slow coincidence circuit gates the 20 channel analyzer which is being fed by the output of the other preamplifier 'A' through a 2.5\(\mu \text{sec}\) delay line.

(E) A Coincidence Sum Spectrometer

A coincidence sum spectrometer was constructed after the design of Hoogenboom.\(^{21}\) A schematic diagram of the circuit is shown in Fig. 4. The 3 inch x 3 inch crystals CR1 and CR2 are shielded from each other by a compton shield of the type described by Bell.\(^{24}\) The output pulses from the preamplifiers \(A_1\) and \(A_2\) are fed to the linear adding network. It is composed of resistances \(R_1\) and \(R_2\), each 1200 ohms, and a helipot \(R_{V1}\) of 500 ohms. A special requirement of the spectrometer is that the energy calibration of both the detectors be the same. This was attained by adjusting the high voltage of one of the photomultiplier tubes. The helipot \(R_{V1}\) serves as a fine adjustment. After amplification the sum pulses are fed into a differential discriminator to select the sum channel. The twenty channel analyzer is gated with these sum pulses. Great care has to be taken in setting the bias of the discriminator of
Fig. 4. The Experimental Arrangement of the "Coincidence Sum Spectrometer."
"D. D. sum" since it influences the shapes of the individual gamma ray peaks.

There are two major advantages of this set up over the single crystal gamma ray scintillation spectrometer.

(a) The pulse distribution shows only one peak, the 'full energy' peak, for specific gamma transition. There is no contribution to the spectrum from processes in which only part of available gamma ray energy is absorbed.

(b) The detection efficiencies of coincident gamma rays are equal.

(F) Beta Ray Spectrometer

The beta ray spectrometer, used for the measurements of internal conversion coefficients and end point energies of beta groups, is of double focusing type first described by Siegbahn and Swartholm.\textsuperscript{19,20} This spectrometer was built by August\textsuperscript{28} and has been described by him in detail. However, the source mounting arrangement has been changed by Page\textsuperscript{29}. A new current control circuit has been constructed by Shinners\textsuperscript{30} after the design of Garwin.\textsuperscript{31} A brief discussion of main features of the magnetic spectrometer will not be out of place here.

\textsuperscript{28}Leon Stanley August, Ph.D. Dissertation submitted to the Louisiana State University (1957).

\textsuperscript{29}M. L. Page, M.S. Thesis to be submitted to the Louisiana State University.

\textsuperscript{30}Carl W. Shinners, M.S. Thesis to be submitted to the Louisiana State University.

Fig. 3. Block Diagram of the "Fast-Slow" Coincidence Circuit.
The magnetic spectrometer has an arrangement for source mounting on one side with the detector displaced from it by 255° in angle. The detector is a plastic phosphor about 3 mm thick. This is coupled to a Dumont 6292 photomultiplier tube by a lucite light pipe. The output of the photomultiplier is taken to a preamplifier which feeds a scaler through a linear amplifier. At a particular setting of the current through the field coil, a predetermined number of counts are taken using a relay device.

The current control circuit gives a current regulation better than 0.001% for long periods. The best vacuum attained inside the magnetic spectrometer was about 7 microns. At this pressure very little scattering of electrons is expected to take place. The best resolution attained with the spectrometer was about 0.9% for 625 KeV conversion line of Cs¹³⁷.

(1) **Calibration of the Instrument.** The momentum calibration of the instrument was done by using Cs¹³⁷ and the well known intense lines of Cs¹³⁴. The conversion electron spectra of these sources were taken and a graph was plotted of counting rate vs. Dekavider readings. The latter are proportional to the voltage across a standard resistor in the magnet current circuit. The $B\beta$ value for each of the conversion lines is taken from the table given by Gerholm. A plot of the $B\beta$ value against the Dekavider reading is made as shown in Fig. 5. The uncertainty in the value of $B\beta$ for each conversion line is less than 0.1%.

---

Fig. 5. Momentum Calibration Curve for Magnetic Spectrometer.
A least square fit through the experimental points satisfies the following relation:

\[ B_R = 7.8131 - 5.9 \text{ gauss-cm} \]

where \( B \) is the Dekavider reading in arbitrary current units.

The extreme stability of the current control circuit enabled us to repeat each reading to better than 0.05\%. From source to source a slight variation in the position of the peaks was observed. This can be explained on the basis of slight variation in the thickness of the different sources and their setting.

(2) **The Cs\textsuperscript{137} Test Spectrum.** In order to check the performance of the spectrometer and to find the cut off point of the scintillation detector, a Fermi-Kuri plot of the continuous spectrum of Cs\textsuperscript{137} was made and is as shown in Fig. 6. The upper curve resulted from the assumption that both 1.17 Mev and 0.51 Mev beta spectra have allowed shapes. It is obvious that lower energy beta group is not allowed. The energy of beta transition was found to be 511 ± 10 Kev, which is in good agreement with previous results. It is known that Fermi plot of this lower energy beta group can be made linear by using the unique first forbidden shape factor \( S_n(W) \).\textsuperscript{33}

\[ S_n(W) = \left( W^2 - 1 + (W_0 - W)^2 \right) \]

where \( W \) is the total energy in \( m_0c^2 \) units and \( W_0 \) is the end point energy in the same units. This shape factor is applicable if \( A \ J = \pm 2 \) and there is a change in parity. The lower curve is the result of applying

\textsuperscript{33}L. M. Langer and R. J. D. Moffat, Phys. Rev. 82, 635 (1951).
Fig. 6. Fermi-Kurie Plot for Cs$^{137}$. Upper Curve is a Normal Fermi Plot. Whereas the Lower is Obtained After Shape Factor Correction.
this factor to the upper curve. However, before applying this factor
the higher energy beta group was subtracted from the total spectrum
which resulted in a straight line up to 135 Kev. The bending in the
straight line below this energy is due to drop in efficiency of the
plastic phosphor.
The $^{134}\text{Cs}$ samples used in this study were made at Oak Ridge by neutron irradiation of $^{133}\text{Cs}$ and were supplied to us in dilute HCl solution. The sources used for the gamma ray spectrum analysis were prepared by evaporating a drop of active solution on aluminum foil or on thin plastic backing. The sources used for the measurement of beta ray spectra were mounted on thin backing of collodion film (5-10$^4$ gms/sq.cm thickness). An acid free solution of $^{134}\text{Cs}$ was prepared and a drop of it was evaporated on the collodion backing. Sources of varying dimensions and strength were prepared and used in the different sets of investigations.

**Gamma Ray Singles Spectra**

A 3 inch x 3 inch NaI(Tl) crystal mounted on a Dumont 6363 photomultiplier tube was used for taking the single spectrum data. Sources were centered 40 cms above the top surface of the crystal. To eliminate beta ray background it was necessary to place a 0.8 gm/cm$^2$ polystyrene absorber between the sample and the crystal. The pulse spectrum obtained with the twenty channel analyzer is shown in Fig. 7. The spectrum was analyzed by the usual peeling procedure. The full energy peaks were drawn by assuming a gaussian shape with proper resolution which depends on the gamma ray energy. The shapes for the
Fig. 7. Gamma Ray Spectrum for the Decay of Cs\(^{134}\) (Source Distance 40Cms.)
Compton distribution and the pair peaks were obtained from the pulse height distributions of standard mono-energetic gamma ray sources run under similar experimental conditions. The standard sources used for this purpose were Cs$^{137}$ and Zn$^{65}$. The 661.6 Kev gamma ray of Cs$^{137}$ was used to construct the Compton distributions for 569, 605, and 800 Kev gamma rays and 1114 Kev gamma ray of Zn$^{65}$ was used to construct Compton distributions and pair peaks for 1038, 1168, and 1367 Kev gamma rays of Cs$^{134}$. The peak at about 605 Kev was found to be broader than that of a monochromatic gamma ray of the same energy and could be analyzed into two peaks corresponding to energies of 569, and 605 Kev. Attempts to analyze the gamma ray spectra below about 300 Kev were made difficult due to the presence of back-scattered gamma rays. However, a gamma ray at about 200 Kev was indicated in the magnetic spectrometer data.

Before calculating the relative gamma ray intensities from the singles spectra, it was necessary to make certain assumptions about the decay scheme as it is quite possible to have summing due to various combinations of cascading gamma rays (the decay scheme assumed was based primarily on the results of the coincidence experiments). From the calculations described by Lazar and Klema,$^{34}$ the loss in the gamma ray intensities from coincident summing was found to be negligible. Therefore, we could find the emission rate of each gamma ray using the relation:

\[ N_0 = \frac{N_p}{\varepsilon_f P_t A} \]

where \( N_0 \) is the number of gamma rays emitted per second by the source, \( N_p \) the area under the photo peak in counts per second, \( \varepsilon_f \) is the total detection efficiency for the source detector geometry used, \( P_t \) the appropriate value for the peak-to-total ratio and \( A \) the correction factor for absorption in the source and any beta absorber used in the measurement. The value for \( \varepsilon_f \) was taken either from Bell's curves or from the theoretically calculated values given by Vegors, Marsden, and Heath. To check the peak-to-total ratio for our crystal, a spectrum of Cs was taken as shown in Fig. 8. The peak-to-total ratio calculated from the curve was found to be 0.54, which was within 1% of the value found by Heath. Therefore, we used for all the gamma rays the values given by Heath for peak-to-total ratio. 'A' was unity in our case since there was almost no loss of energy.

The best values for the energies and the intensities of various gamma rays, as found in this work, have been shown in Table I. Also the values found by other authors, are tabulated. Only those workers, who have made intensity measurements for the various gamma rays, have been quoted. No indication was found in this work for the 960 and 1570 KeV gamma rays reported by Girgis et al.

---

35 R. Bell, Scintillation Spectrometer Handbook.
Fig. 8. Gamma Ray Spectrum for the Decay of Cs$^{137}$. Dotted Curve Shows the Data After Back Scatter Correction.
Table I

Summary of the Experimental Data for the Relative Intensity of the Various Gamma Rays of Cs\textsuperscript{134}

<table>
<thead>
<tr>
<th>Joshi et al\textsuperscript{10}</th>
<th>Bashilov\textsuperscript{38}</th>
<th>Verhaeghe et al\textsuperscript{39}</th>
<th>Foster et al\textsuperscript{40}</th>
<th>Keister et al\textsuperscript{13,14}</th>
<th>Johnson\textsuperscript{41}</th>
<th>Girgis et al\textsuperscript{15}</th>
<th>Present Work</th>
</tr>
</thead>
<tbody>
<tr>
<td>( E^* (\text{Kev}) )</td>
<td>( E^* )</td>
<td>( I^* )</td>
<td>( E^* )</td>
<td>( I^* )</td>
<td>( E^* )</td>
<td>( I^* )</td>
<td>( E^* )</td>
</tr>
<tr>
<td>200.4 ± 1.5</td>
<td>4</td>
<td>204 ± 5</td>
<td>10</td>
<td>208.3 ± 1.5</td>
<td>4</td>
<td>210? Weak</td>
<td>200 ± 1.5</td>
</tr>
<tr>
<td>475 ± 15</td>
<td>3.5</td>
<td>475 ± 15</td>
<td>4</td>
<td>475 ± 15</td>
<td>4</td>
<td>473 ± 2</td>
<td>1.8 ± 0.5</td>
</tr>
<tr>
<td>553 ± 7</td>
<td>563 ± 2</td>
<td>10 ± 1</td>
<td>565.2 ± 0.7</td>
<td>15</td>
<td>562 ± 2</td>
<td>14</td>
<td>563 ± 1</td>
</tr>
<tr>
<td>571 ± 7</td>
<td>21</td>
<td>569 ± 2</td>
<td>18 ± 2</td>
<td>570.9 ± 0.7</td>
<td>20</td>
<td>569 ± 1</td>
<td>12</td>
</tr>
<tr>
<td>607 ± 7</td>
<td>604 ± 2</td>
<td>100</td>
<td>605.8 ± 0.8</td>
<td>100</td>
<td>604 ± 1</td>
<td>100</td>
<td>605 ± 1</td>
</tr>
<tr>
<td>794 ± 3</td>
<td>100</td>
<td>796 ± 3</td>
<td>103 ± 10</td>
<td>797 ± 0.6</td>
<td>100</td>
<td>796 ± 1</td>
<td>72</td>
</tr>
<tr>
<td>802 ± 3</td>
<td>8 ± 1</td>
<td>802.2 ± 0.6</td>
<td>15</td>
<td>802 ± 1</td>
<td>11</td>
<td>801 ± 2</td>
<td>18 ± 4</td>
</tr>
<tr>
<td>1027 ± 15</td>
<td>1038 ± 4</td>
<td>1.1 ± 0.6</td>
<td>1034.5 ± 2.0</td>
<td>4</td>
<td>1035 ± 3</td>
<td>5</td>
<td>1038 ± 4</td>
</tr>
<tr>
<td>1164 ± 10</td>
<td>4</td>
<td>1166 ± 4</td>
<td>1.7 ± 0.6</td>
<td>1168 ± 3</td>
<td>4</td>
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<td>3.0 ± 0.4</td>
</tr>
<tr>
<td>1368 ± 5</td>
<td>5</td>
<td>1367 ± 5</td>
<td>2.8 ± 0.6</td>
<td>1370 ± 3</td>
<td>4</td>
<td>1369 ± 3</td>
<td>5</td>
</tr>
<tr>
<td>1401 ± 15</td>
<td>1570 ± 20</td>
<td>0.12 ± 0.05</td>
<td>1570</td>
<td>0.05</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>


\( \text{\textsuperscript{39}} \) J. Verhaeghe and J. Demuyneck, Compt. Rend. 239, 1374 (1954).


\( \text{\textsuperscript{41}} \) K. E. Johnson, Arkiv Fysik 10, 247 (1956).

\*E = Energy; \**I = Intensity.
The spectrum of Cs$^{134}$ was also taken by placing the source at different distances from the crystal. Fig. 9 shows the spectrum for the energy region of about 300 to 2000 Kev. The solid line represents the spectrum with the source at 3.6 cms from the crystal and the dotted line represents the spectrum with the source at 30 cms from the crystal. Sum peaks at 1168, 1401, 1640, and 1970 Kev can be easily seen, confirming most of the results obtained by Lu et al.$^{42}$ and Girgis.$^{15}$ The shape of the spectrum around 1770 Kev indicates a sum peak at 1770 Kev. An analysis of the high energy region of the spectrum is shown in Fig. 10. This was done by using Na$^{22}$ and Co$^{60}$ sum peaks as reference standards. This analysis yielded three sum peaks at 1640, 1770, and 1970 Kev as shown in the figure.

The magnitude of the sum peaks can be easily obtained by using the following method. Suppose a sum peak involves a cascade of two gamma rays. The intensity of the sum peak is then given by:

$$N_{\text{sum}} = N \varepsilon_1 \varepsilon_2 \omega^2$$

where $N$ is the intensity of the cascade, $\varepsilon_1$ and $\varepsilon_2$ are the photo-peak efficiencies for the two gamma rays $\gamma_1$ and $\gamma_2$ involved in the cascade resulting in the sum peak $\gamma_{12}$, $\omega$ is the fractional solid angle subtended at the source position by the crystal (directional correlation effects assumed negligible).

If the summing involves three cascading gamma rays $\gamma_1$, $\gamma_2$, and $\gamma_3$, respectively the spectra will consist of the gamma rays $\gamma_1$, $\gamma_2$, and $\gamma_3$.
Fig. 9. Gamma Ray Spectra for the Decay of Cs$^{134}$ at Different Distances.
Fig. 10. High Energy Part of the Gamma Ray Spectrum of Fig. 9 after Careful Analysis (Source Distance 3.6 Cms.)
3 and the sum peaks $\gamma_{12}$, $\gamma_{23}$, $\gamma_{13}$. There will also be a sum peak at an energy corresponding to the sum of all three gamma rays. Let us denote it by $\gamma_{123}$. The intensity of the various sum peaks is given by:

$$N_{ij} \propto n \varepsilon_1 \varepsilon_j \omega^2$$  \hspace{1cm} (2)

and

$$N_{123} = N \varepsilon_1 \varepsilon_2 \varepsilon_3 \omega^3$$  \hspace{1cm} (3)

Table II
Possible Combinations Giving High Energy Sum Peaks

<table>
<thead>
<tr>
<th>Sum Peaks (Kev)</th>
<th>Possible Combinations for Sum Peaks (Kev)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1643</td>
<td>(1038, 605), (1168, 475), (475, 563, 605)</td>
</tr>
<tr>
<td>1770</td>
<td>(1168, 605)</td>
</tr>
<tr>
<td>1970</td>
<td>(1168, 800), (1367, 605), (605, 563, 802), (569, 605, 797)</td>
</tr>
</tbody>
</table>

No evidence was found for the 1640 (<0.05), 1770 (<0.05), and 1970 (<0.04) Kev cross-over transitions reported by French and Goodrich. 16

From the calculations of the intensities of the sum peaks obtained in the pulse spectrum taken with the sources at small distances from the crystal, it is believed these reported peaks were entirely due to summing.

Coincidence Spectrum Analysis

(a) Gamma-Gamma Coincidences

Gamma-gamma coincidence measurements were made by French 22 using a "fast-slow" coincidence circuit having a resolving time "\( \tau \)" of 200 Nano second (1 Nano second = 10^-9 sec). The source was viewed by two 3 inch x 3 inch NaI(Tl) crystals with their axes at 90° to each other. A Compton shield similar to that described by Bell 24 was used for
shielding one crystal from the other. For individual runs the single channel analyzer window was set on the principal gamma ray peaks, and the gamma ray coincidence spectra was recorded in the twenty channel analyzer. Subsequent to French's analysis of his gamma-gamma coincidence data, it has become clear that his data is sufficiently reliable to justify more elaborate and complete analysis. A complete re-analysis of the data was undertaken using carefully the complete experimental pulse spectra for the monochromatic gamma rays. Summing effects were carefully scrutinized.

Fig. 11 shows the gamma ray spectra taken in coincidence with 605 Kev energy gamma ray. The full energy peaks were analyzed in the same manner as in the single's spectra. Care was taken to construct proper Compton distributions and pair peaks for the various gamma rays. The peeling was started from the high energy end and was successively pursued towards the lower energy side. However, Fig. 11 shows only the full energy peaks. The peaks at 800, 1038, and 1367 Kev were clearly resolved. The peaks at 475 and 1168 Kev were obtained only after proper subtractions were carried out. A broad peak was resolved around 605 Kev energy. As in the singles spectra, it was attributed to the gamma rays at 563-569 and 605 Kev. A part of the peak at 605 Kev in the coincidence spectrum has been caused by the contribution of the 563-569 Kev gamma rays falling in the window of the single channel analyzer setting. The rest of this peak is due to Compton of the 800 Kev gamma ray in the single channel analyzer window, which is in coincidence with 605 Kev gamma ray. Thus, there are few, if any, true
Fig. 11. Gamma Ray Spectra in Coincidence with 605 keV Gamma Ray.
605-605 Kev gamma ray coincidences and the number of transitions from the 1773 Kev level to 1168 Kev level in the finally proposed decay scheme must be quite small.

To determine the intensities of the various gamma rays from the coincidence data, the following general equation was used:

$$ N_{E}(E') = N_{w} \varepsilon_{p}(E') \omega(E') e^{-ud} \left\{ f_{E}(E') A + \xi f_{1} B_{j} \right\} W(\Theta) \quad (4) $$

where $N_{E}(E')$ is the peak area of the gamma ray $E$ observed in coincidence with the gamma ray $E'$, $\varepsilon_{p}(E')$ and $\omega(E')$ are the photo-peak efficiency and the solid angle for the detection of the gamma ray $E'$, $e^{-ud}$ is the fraction of the gamma ray $E'$ transmitted through the beta absorber and $N_{w}$ is the observed counting rate in the window of the single channel analyzer. The factor $f_{E}(E')$ is the fraction of the gamma rays of energy $E$ which are in coincidence with the gamma ray of energy $E'$, $A$ is the fraction of the observed rate in the window due to the gamma ray $E$ with which coincidences are being measured and may be obtained from the singles spectra. The term $\xi f_{1} B_{j}$ corrects for Compton pulses in the window from higher energy gamma rays which are also in coincidence with $E$. $B_{j}$ is the fraction of counts in the window due to the higher energy gamma ray Comptons and $f_{1}$ is the fraction of these gamma rays which are in coincidence with the gamma ray of energy $E'$, as determined from the decay scheme. $W(\Theta)$ is the angular correlation function of the two gamma rays integrated over the face of the crystal. This was assumed to be unity in our calculations.

Corrections have been applied to the coincidence peaks observed at energies of 1038, 1168, and 1367 Kev due to possible summing combinations.
which may result in these energies. Formula (4) was suitably modified and was used to make all the corrections mentioned.

The gamma ray spectrum coincident with 800 Kev gamma ray is shown in Fig. 12. A careful subtraction indicates a broad peak in the neighborhood of 605 Kev energy, which can be resolved into two gamma rays of energies 569 and 605 Kev. The peak observed at 1168 Kev has a finite but small contribution due to the summing in the crystal on the twenty channel analyzer side. The peak at 800 Kev could be explained by the random coincidences between 802-797 Kev gamma rays and the contribution of the 1168 Kev gamma ray Comptons which are in coincidence with 800 Kev gamma ray.

Coincidence spectra was also taken with 1038, 1168, and 1367 Kev gamma rays and are shown in Figs. 13, 14, and 15, respectively. In these spectra, the counts in the window had to be corrected for the contribution of sum pulses. Equation (2) discussed earlier was used for this purpose.

The peak at 605 Kev in Fig. 13 is the only genuine coincidence peak. Peaks appearing at 475 and 800 Kev have been found to arise due to the finite contribution of 1168 Kev gamma ray and (563, 605) Kev gamma ray sum peak in the window of the single channel analyzer set for 1038 Kev peak.

Fig. 14 shows coincidence peaks at 800, 605, and 475 Kev. A considerable contribution to the 1168 Kev gamma ray was found to arise due to summing of 569 and 605 Kev gamma rays. Also the Compton distribution of 1367 Kev lies underneath the 1168 Kev peak. All these contributions were corrected for in the manner mentioned earlier. The
Fig. 12. Gamma Ray Spectra in Coincidence with 800 Kev Gamma Ray.
Fig. 13. Gamma Ray Spectra in Coincidence with 1038 keV Gamma Ray.
Fig. 14. Gamma Ray Spectra in Coincidence with 1168 KeV Gamma Ray.
Fig. 15. Gamma Ray Spectra in Coincidence with 1367 KeV Gamma Ray.
peak at 569 Kev has been found to arise merely due to the coincidences between Comptons of the sum pulses (605, 797), (605, 802) (which lie under 1168 Kev peak) with 569 or 563 Kev gamma rays, respectively.

In Fig. 15 the peak at 800 Kev can be fully explained by a number of possible random coincidences. Thus, only the 605 Kev gamma ray is in coincidence with 1367 Kev gamma ray.

The relative intensities of the transitions from the coincidence data has been estimated from a knowledge of the counts in the photo peak, the detection efficiency and peak to total ratio. Negligible loss in intensity was found due to any conversions of the gamma rays. These results have been summarized in Table III. The table also gives the relative intensities for the various gamma rays as obtained in the coincidence as well as the singles data. It can be noted that a good agreement exists for the intensity values.

(b) Beta-Gamma Coincidences

The beta-gamma coincidence study was done by French to get direct information about the placing of the various beta groups in the decay scheme. He observed 655 Kev beta group to be in coincidence with 605 Kev and 800 Kev gamma rays as shown in Figs. 16 and 17. It was not possible to detect any high energy or low energy beta groups because of the following reasons:

(a) Low intensity of these beta groups.

(b) A poor resolution of the set up as compared to the magnetic spectrometer.
### Table III

Summary of the Coincidence Data

<table>
<thead>
<tr>
<th>Gamma Ray Energy (Kev)</th>
<th>Intensities Relative to 605 Kev as 100 Units</th>
<th>Gamma Rays Appeared in Coincidence</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>From Singles Data</td>
<td>Best Value From Coincidence Data</td>
</tr>
<tr>
<td>475±5</td>
<td>1.5±0.3</td>
<td>1.27±0.3</td>
</tr>
<tr>
<td>569±3</td>
<td>22±3</td>
<td>19±3</td>
</tr>
<tr>
<td>605±3</td>
<td>100</td>
<td>96±10</td>
</tr>
<tr>
<td>800±4</td>
<td>98±3</td>
<td>90±9</td>
</tr>
<tr>
<td>1038±6</td>
<td>1.2±0.3</td>
<td>1.02±0.15</td>
</tr>
<tr>
<td>1168±4</td>
<td>2.7±0.3</td>
<td>2.9±0.4</td>
</tr>
<tr>
<td>1367±4</td>
<td>3.6±0.4</td>
<td>3.5±0.45</td>
</tr>
</tbody>
</table>
Fig. 16. Beta Ray Spectra in Coincidence with 605 Kev Gamma Ray.
Fig. 17. Beta Ray Spectra in Coincidence with 800 keV Gamma Ray.
Measurements with the Magnetic Spectrometer

The magnetic spectrometer has been discussed in Chapter II. It was used to study the internal conversion lines and the continuous beta ray spectra.

Fermi-Kurie plots of the various beta ray spectra observed are shown in Fig. 18 and 19. A Fortran program was written for an IBM-650 computer which analyzed the raw data from the magnetic spectrometer into a Fermi plot. This procedure enabled an accurate and consistent analysis of the relative intensities and the end point energy without personal prejudice. Analysis in the low energy region with this program showed a marked difference from the best that could be done manually.

Fig. 18 shows a typical Fermi-Kurie plot for the higher region of the beta spectra. Three beta groups with end point energies of 655, 892, and 1453 Kev were found. A very careful study was made of the region around 600 to 700 Kev but no indication was obtained for a beta group of 680 Kev energy reported by earlier workers.\textsuperscript{14,40}

Fig. 19 shows a typical Fermi plot of beta-distribution up to about 600 Kev. This curve is found to have two distinct slopes having end point energies of 655 and 410 Kev. No indication was found for a 280 Kev beta group as reported by earlier groups.\textsuperscript{43,44} Detection of a beta ray group with end point energy of 86 Kev was not possible because of low detector efficiency in this region.

\textsuperscript{44}C. L Peacock, NP-6325.
Fig. 18. Fermi-Kurie Plot of Cs$^{134}$ (High Energy Region). The Data on Analysis Shows Three Beta Groups of End Point Energies 1453, 892 and 655 Kev.
Fig. 19. Fermi-Kurie Plot of Cs$^{134}$ (Low Energy). This Curve Shows Two Slopes Which on Analysis Give a Beta Group of 410 Kev as its End Point Energy.
The energy and the intensities of the various beta ray groups have been given in Table IV. Also the results of some of the earlier workers are presented for comparison. An assumption was made regarding the intensity of 86 Kev beta ray group to fit the coincidence and sum data.

The magnetic spectrometer was also used for the internal conversion spectra of the gamma rays from the decay of $^{134}\text{Cs}$. Figs. 20 and 21 show the conversion spectra for the low and high energy regions, respectively. The value of the internal conversion coefficients were calculated and have been given in Table V. The values were obtained by using "comparison method." Similar sources of $^{134}\text{Cs}$ and $^{137}\text{Cs}$ were used and conversion lines for each were obtained using the magnetic spectrometer. Fig. 22 gives the internal conversion spectra obtained for $^{137}\text{Cs}$. The sources (No. 1) used for obtaining these conversion lines were very strong and could not be used for obtaining gamma ray scintillation spectra. Therefore, two relatively weak but similar sources (No.2) of $^{134}\text{Cs}$ and $^{137}\text{Cs}$ were prepared and parts of the conversion spectra were taken for only the intense gamma rays as shown in Figs. 23 and 24. These sources were still strong, and we could not obtain the gamma ray spectra with the sources any closer than 98 Cm from the 3 inch x 3 inch NaI(Tl) crystal. Another pair of weak sources (No. 3) of $^{134}\text{Cs}$ and $^{137}\text{Cs}$ were prepared (about 6$\mu$ c), and their complete gamma rays spectra were recorded. These spectra for sources (2) and (3) are shown in Figs. 7, 8, 25, and 26. The spectra shown in Fig. 7 has been completely analyzed for the relative intensity of the various gamma rays as discussed earlier. The absolute values of the intensities of the various gamma
Table IV

Energy and Intensity of the Various Beta Groups.

<table>
<thead>
<tr>
<th>E*</th>
<th>l**</th>
<th>E*</th>
<th>l**</th>
<th>E*</th>
<th>l**</th>
<th>E*</th>
<th>l**</th>
<th>Present Investigation</th>
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<tbody>
<tr>
<td>88±4</td>
<td>25</td>
<td>80±3</td>
<td>28</td>
<td>83±3</td>
<td>32±6</td>
<td>86</td>
<td>20</td>
<td>86</td>
</tr>
<tr>
<td>210±10</td>
<td>3</td>
<td>210 None</td>
<td>210 None</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>409±4</td>
<td>5</td>
<td>282 2.8</td>
<td>280 2.1</td>
<td></td>
<td></td>
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<tr>
<td>654±6</td>
<td>75±5</td>
<td>650±5</td>
<td>56</td>
<td>655±2</td>
<td>50</td>
<td>652 75.5</td>
<td>655±3</td>
<td>71±1</td>
</tr>
<tr>
<td>685±10</td>
<td>8</td>
<td>683±4</td>
<td>13±6</td>
<td>680 None</td>
<td>680 None</td>
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</tr>
<tr>
<td>886 1.5</td>
<td>892±5</td>
<td>0.7</td>
<td>1450 0.2</td>
<td>1453±10</td>
<td>0.13</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*E = Energy.
**l = Intensity.
Fig. 20. Conversion Spectra for the Decay of $\text{Cs}^{134}$ (Low Energy Region).
Fig. 21. Conversion Spectra for the Decay of Cs$^{134}$ (High Energy Region).
Fig. 22. Conversion Spectra for the Decay of $\text{Cs}^{137}$ (Source No. 1).
Fig. 23. Conversion Spectra for the Decay of Cs$^{134}$ (Source No. 2).
Fig. 24. Conversion Spectra for the Decay of Cs$^{137}$ (Source No. 2).
Fig. 25. Gamma Ray Spectra for the Decay of Cs\textsuperscript{134} (Source No. 2).
Fig. 26. Gamma Ray Spectra for the Decay of Cs$^{137}$ (Source No. 2).
rays for sources No. 1 were obtained by using the normalization factors obtained from the comparison of the various sources.

Knowing the area under the conversion peaks from the magnetic spectrometer data and the absolute intensities of the corresponding unconverted gamma rays from the scintillation spectrometer data, the value of the K-conversion coefficient for the 605 KeV gamma rays of Cs$^{134}$ was obtained using the following relation:

$$\alpha_{K605} = \alpha_{K662} \frac{N(e_k)_{605}}{N(e_k)_{662}} \frac{N(\gamma)_{662}}{N(\gamma)_{605}}$$

where $\alpha_{K662}$ is the conversion coefficient of 662 KeV gamma ray of Cs$^{137}$, $N(e_k)_{605}$ and $N(e_k)_{662}$ are the normalized areas under the conversion peaks of 605 and 662 KeV gamma rays, $N(\gamma)_{605}$ and $N(\gamma)_{662}$ are the unconverted gamma ray intensities for 605 and 662 KeV gamma rays, respectively.

Using $\alpha_{K662} = 0.096$ as measured by Azuma,$^{45}$ the K-conversion coefficient of 605 KeV gamma ray was estimated. A value of $(5.6 \pm 0.5) \times 10^{-3}$ was obtained for the K-conversion coefficient of 605 KeV gamma ray. A theoretical estimate taking this transition to be pure E2 was found to be $5.15 \times 10^{-3}$ using Rose's tables.$^{46}$ The angular correlation work done by various workers$^{47,48,49}$ points to a $2^+$ assignment for the 605 KeV

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level. The $2^+$ assignment is further supported by the $\log ft$ value of 1453 Kev beta group leading to this level as will be discussed in the next chapter. It thus seems fair to assume that the 605 Kev transition is pure E2. Using Rose's tables the theoretically expected value for $K/L + M$ ratio for 605 Kev was calculated. The experimental values of $\alpha_K$ and $K/L + M$ for all other gamma rays were normalized taking the theoretical values of K-conversion coefficients and $K/L + M$ of 605 Kev as standard. Table V shows these values along with the theoretical ones. Also the possible assignments of the multipolarities to the various gamma rays are shown.

A slight bump in the continuous beta ray spectra was repeatedly observed in the neighborhood of the 200 Kev gamma ray region, and this bump was found to have an intensity of $1 \pm 0.5$. It will be discussed later on in Chapter IV.

**Coincidence Sum Spectrometer Measurements**

In order to get clear evidence about the higher energy levels of Ba$^{134}$, coincidence sum spectrometer was used. It has been discussed in Chapter II. The width of the window of the single channel analyzer set for the sum peak was always kept narrow. In the interpretation of the sum spectra great care was taken about the possible summing of the Compton peaks with certain coincident gamma rays. The possible sum combinations have been shown dotted in the figures for the various sum spectra which are discussed below:

The sum spectra obtained by setting the "D.D. sum" at 1970 Kev is shown in Fig. 27. It shows two prominent gamma-gamma cascades (1168-800) and (1367-605) Kev. There is a considerable contribution to
### Table V

K-Conversion Coefficients and $K/(L + M)$ Ratio for Cs\textsuperscript{134}

<table>
<thead>
<tr>
<th>Transition (Kev)</th>
<th>$\lambda_k^{(exp)} \times 10^3$</th>
<th>Theoretical Value of $\lambda_k^{(exp)}$ after Rose \textsuperscript{46} $\times 10^3$</th>
<th>Exp. Value of $K/L+M$</th>
<th>Multipole Order (adopted)</th>
</tr>
</thead>
<tbody>
<tr>
<td>563±1</td>
<td>8±1</td>
<td>2.1</td>
<td>5.9</td>
<td>E2 + M1</td>
</tr>
<tr>
<td>569±0.5</td>
<td></td>
<td></td>
<td></td>
<td>M1</td>
</tr>
<tr>
<td>605±0.4</td>
<td>5.15</td>
<td>1.9</td>
<td>5.15</td>
<td>E2</td>
</tr>
<tr>
<td>800±0.7</td>
<td>2.5±0.5</td>
<td>1.03</td>
<td>2.6</td>
<td>E2</td>
</tr>
<tr>
<td>1038±0.5</td>
<td>1.45±0.2</td>
<td>1.45</td>
<td>5.1</td>
<td>E2</td>
</tr>
<tr>
<td>1168±0.5</td>
<td>0.8±0.2</td>
<td>0.48</td>
<td>1.1</td>
<td>E2 + E1</td>
</tr>
<tr>
<td>1367±1</td>
<td>0.7±0.15</td>
<td>0.36</td>
<td>0.79</td>
<td>E2</td>
</tr>
</tbody>
</table>

*Normalized to theoretical E2 value for 605 Kev transition.
Fig. 27. Coincidence Sum Spectra With the Single Channel Analyzer Set at 1970 Kev.
these sum peaks due to the possible triple cascades (563, 605-800) Kev and (569, 605-797) Kev; this indirectly confirms a level at 1970 Kev.

Fig. 28 shows the sum spectra obtained by setting the single channel at 1770 Kev. An increase in the general background results and is due to some contribution of the Comptons of 1970 Kev gamma ray falling underneath the 1770 Kev peak. The peaks at 1168 and 605 Kev indirectly points to the existence of 1770 Kev level. The peaks at 1367, 950, 800, and 400 Kev could be attributed to Compton peak summing.

Fig. 29 shows the sum spectra obtained by setting the single channel at 1640 Kev energy. This spectrum shows peaks at 475, 605, 1038, and 1168 Kev energy which are due to 605-1038 and 475-1168 gamma ray cascades. The rest of the peaks are due to summing of Compton peaks with some gamma rays. The above cascades verify the level at 1640 Kev.

Fig. 30 shows coincidence sum spectra obtained by setting single channel analyzer at 1401 Kev energy. This spectra shows gamma peaks at 605, 800, and 1401 Kev; this indicates a level at 1401 Kev.

**Life Time Measurements by Delayed Coincidence Method**

The "fast-slow" coincidence spectrometer discussed in Chapter 11 was used in an attempt to find the life times of one of the levels in Ba$^{134}$. The level studied was the one at 605 Kev since it provided the maximum counting to warrant such a study. As 800 Kev and 605 Kev gamma rays have been found to be E2 transitions, the level at 605 Kev was expected to be delayed about $10^{-10}$ sec. To check this, the coincidences were taken between 800 and 605 Kev gamma rays as a function of the delay time, and a curve was plotted, the delay in n-sec vs. counts as shown
Fig. 28. Coincidence Sum Spectra With the Single Channel Analyzer Set at 1770 Kev.
Fig. 29. Coincidence Sum Spectra With the Single Channel Analyzer Set at 1640 Kev.
Fig. 30. Coincidence Sum Spectra With the Single Channel Set at 1401 Kev.
in Fig. 31. It indicates that the delay between 800 and 605 Kev gamma rays has to be less than about 0.5 n-sec.

Fig. 32 shows the delay curve between 1367 and 605 Kev gamma rays which are in coincidence. This shows that the possible delay between the two gamma rays is less than 0.5 n-sec. Thus, it is concluded that the life time of the 605 Kev level is less than 0.5 n-sec.
Fig. 31. Delay Curve of 800-605 Kev Gamma Rays.
Fig. 32. Delay Curve of 1367-605 Kev Gamma Rays.
CHAPTER IV
DISCUSSION OF THE DECAY SCHEME

The total decay energy of Cs\textsuperscript{134} has been found to be 2.07 Mev.\textsuperscript{8} Using this information and incorporating the experimental results obtained in our measurements, the decay scheme shown in Fig. 33 was postulated.

The level at 605 Kev is indicated by the existence of a feeble beta group with end point energy of 1453 Kev. This level has been confirmed by the observance of the 605 Kev gamma ray in the decay of La\textsuperscript{134}.\textsuperscript{15} The beta-gamma and the gamma-gamma coincidence results obtained in this investigation point further to the existence of a 605 Kev level decaying to the ground state with a gamma ray of the same energy.

The level at 1168 Kev is supported by the coincidence data. Coincidences between 1168 Kev and 800 Kev gamma rays were observed. Also 800 Kev and 605 Kev gamma rays were found to be 100\% in coincidence. As this coincidence could account for about 98\% of 800 Kev gamma ray, this almost excludes the possibility of a level at 800 Kev. This conclusion is further supported by the fact that the nuclei in the range 60 \(\leq A \leq 150\) (having a neutron or a proton number different from that of the closed shell) are not found to have the ratio of the energies of the second to the first excited state appreciably less than 2. Thus,
Fig. 33. Decay Scheme of Cs$^{134}$ From the Present Work. The Energy, the Intensities and the Log ft Values of the Various Beta Groups Are Shown.
a level at 1168 is indicated. It is further confirmed by the detection of a 892 Kev beta-group and the observance of a sum peak at 1168 Kev in the gamma spectra.

The observance of a 655 Kev beta group in the magnetic spectrometer data confirms the existence of a level at 1402 Kev. This level is also implied by the coincidences observed between the 655 Kev beta group and two gamma rays of energies 605 and 800 Kev. The coincidences observed between 800 and 605 Kev gamma rays and the sum peak at 1401 Kev in the gamma ray spectra taken at close distances, further supports this level.

The level at 1643 Kev is suggested by the observation of the 410 Kev beta group. It is further supported by the sum spectrum which shows a peak at 1643 Kev arising due to the summing of the various combinations of gamma rays observed in the single spectra. The observation of the coincidences between the 1038 and the 605 Kev gamma rays further points to the existence of the same level.

The level at 1773 Kev is suggested by the observation of a sum peak at 1770 Kev in the sum spectrum. The coincidences between 605 and 1168 Kev gamma rays also suggest this level. The sum peak corresponding to 1770 Kev is found to be less intense than that of 1640 Kev. This fact is supported by the coincidence data which implies that the intensity of the gamma ray leaving the 1773 Kev level is only 0.6. This observation does not support the observed intensity of 280 Kev beta group found by Peacock to be 2.8%. The Fermi-Kurie plot of the magnetic spectrometer data in this region shows no evidence of a beta group (≤0.2%).
The level at 1970 Kev is confirmed by the coincidences observed between 800 and 1168 Kev and 1367 and 605 Kev gamma rays, respectively. The sum spectra and the coincidence sum spectra confirms the existence of this level. In the magnetic spectrometer data, a small bump for 200 Kev gamma ray has been observed. It is proposed that the level at 1773 Kev is fed by ~200 Kev gamma ray from 1970 Kev level and its intensity can be (1 ± 0.5)%.

The assignment of spins and parities to the various levels can be done by the analysis of internal conversion coefficients of the various gamma rays and by the log ft values of the various beta groups. The ground state spin of Cs$^{134}$ has been measured as 4$^+$. The characters of the ground state of Ba$^{134}$ are 0$^+$ which agree with the usual behavior of even-even nuclei.

The internal conversion coefficient for the 605 Kev transition from the first excited state is quite close to the theoretically expected value for E2 transition. This suggests 0$^+$, 1$^+$, and 2$^+$ assignment for this level. The log ft value of 1453 Kev beta group corresponding to this level is found to be about 13 which indicates that it is a second forbidden transition with $\Delta J = \pm 2$ with no change in parity. Thus, the characteristics of the level at 605 Kev are 2$^+$. The angular correlation measurements done by Everett and Glaubman supports 2$^+$ assignment to this level.

50 S. A. Moszkowski in "Beta and Gamma Ray Spectroscopy."

The behavior of low lying levels in even-even nuclei has been interpreted in terms of two types of collective motions, a "free vibration model" by Scharff-Goldhaber and Weneser and a "shape unstable model" by Wilets and Jeans. The latter authors used the equations of Bohr and Mottelson to calculate a value of 0.34 for $E_1/\hbar \omega$ for $^{134}$Ba, where $E_1$ is the energy of the first excited state (605 Kev) and $\omega$ is the characteristic phonon frequency of a theoretically undeformed nucleus. The intermediate value (between zero and one) of $E_1/\hbar \omega$ together with the ratio $E_2/E_1 = 1.93$ (this was assumed to be 2.32 by Wilet and Jean because 1168 level was uncertain whereas the 1401 Kev level was regarded as the second excited state) of the energy of the second to the first excited state probably indicates nearly pure harmonic quadrupole vibration of the core, with a small contribution from the six protons beyond the closed shell of magic number 50. As has been stressed by Scharff-Goldhaber and Weneser for such cases the cascade processes between the second and first excited levels proceed by $E2$ radiation with some small $M1$ admixture. Thus the 563 Kev transition is most probably a $E2 + M1$ mixture. The conversion coefficient of 563-569 Kev gamma ray as found in these experiments (Table V) also lies between the values corresponding to $M1$ and $E2$ transitions. This measured value can be obtained from theoretical conversion coefficients if we assume 569 Kev as pure $M1$ transition whereas 563 Kev transition to be 80% $E2$ and 20% $M1$. This confirms the theoretically expected assignment of 563 Kev gamma ray as stressed by Scharff-Goldhaber and Weneser.
The character of the level at 1168 Kev has to be $0^+$, $1^+$, or $2^+$ to fit the assignment of the 563 Kev gamma ray transition. Since the log-ff value of 892 Kev beta group is 11.4, this transition is second forbidden with $\Delta J = \pm 2$, with no change in parity. Therefore, 1168 Kev is most probably a $2^+$ level. This assignment is confirmed by the angular correlation work of various groups. It might be remarked that Scharff-Goldhaber and Weneser further stress that for a sequence $0^+, 2^+, 2^+$ the crossover transition ($2^+ \rightarrow 0^+$) proceed by E2 transition. Thus, 1168 Kev transition is expected to be an E2. The internal conversion coefficient of 1168 Kev gamma ray as found in the present investigation (Table V) lies between the theoretically expected value for E1 and E2 transition. This requires 20% of one of the 1168 Kev gamma ray as E1 and 80% of the other 1168 Kev gamma ray to be E2 (there are two gamma rays of energy 1168 Kev as found from coincidence measurement). Thus, the 1168 Kev transition from the 1168 Kev level is E2 in conformity with the theoretically expected value.

The next level at 1402 Kev does not have any transition to the ground state ($< 0.2$). This indicates that this level must have a spin $\geq 3$. The transition between 1402 and 605 Kev is an E2 transition as indicated by the measurement of the K-conversion coefficient of the 800 Kev gamma ray which requires $2^+$, $3^+$, or $4^+$ assignment for this level. The 655 Kev beta group feeding this level is found to be the most intense. This suggests that 655 Kev beta group should be an allowed transition even though the measured log ft value for this group is high. Thus, the level at 1402 Kev should be either $3^+$ or $4^+$. The angular
correlation work of the various groups$^{47,48,49}$ favors a 4+ assignment to this level.

The level at 1643 Kev has two transitions leaving it. The 1038 Kev gamma ray is found to be an E2 transition from conversion coefficient measurements (Table V), and the 475 Kev gamma ray has been previously found to be a E2 transition by Schmidt et al.$^{14}$ Thus, the 1168 Kev level can be 0+, 1+, 2+, 3+, or 4+. This level is fed by the beta group of energy 410 Kev with a log ft value of about 10. This is most probably a second forbidden transition with $\Delta J = \pm 2$, with no change in parity which suggests a 2+ character to this level.

The 1168 Kev transition between 1773 and 605 Kev levels is most probably an El transition as found from the K-conversion coefficient measurement of the 1168 Kev gamma rays (discussed earlier). This suggests 1−, 2−, or 3− assignment to this level. As there is no direct transition observed between the 1773 Kev level and the ground state, this level may be either 2− or 3−.

The level at 1970 Kev is fed by the 86 Kev beta group which seems to be an allowed transition even though its log ft value is high. This suggests an assignment of 3+ or 4+ to it. The 800 Kev gamma ray transition from this level is most probably an E2 transition, which favors an assignment of 4+ to this level. This assignment is also confirmed by the angular correlation work of various groups.$^{47,49}$
BIBLIOGRAPHY

August, Leon Stanley, Ph.D. dissertation submitted to the Louisiana State University (1957).


Bell, P. R., Scintillation Spectroscopy Handbook, private communication.


Elliot, L. G. and Bell, R. E., Phys. Rev. 72, 969 (1947).


Johnson, K. E., Arkiv Fysik 10, 247 (1956).
Nuclear Data Sheets, National Research Council, Washington, D.C.
Page, M. L., M.S. thesis to be submitted to the Louisiana State University.
Peacock, C. L., NP-6325.
Shinners, Carl W., M.S. thesis to be submitted to Louisiana State University.


Wilet, L. and Jean, M., Phys. Rev. 102, 788 (1956).

GENERAL REFERENCES

Alder, K., Bohr, A., Huus, T. M., Mottelson, B. and Winther, A., Coulomb Excitation, Rev. of Mod. Phys. 28, No. 4, 432 (1956).


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Title of Thesis: Decay Scheme of Cs$^{134}$

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Dean of the Graduate School

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Date of Examination:

July 6, 1960