STUDY OF INTERNAL CONVERSION PROCESS

IN

^{207}Pb AND ^{131}Cs

A Thesis

Submitted to the

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at the University of Manitoba

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by

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

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ABSTRACT

A new approach has been adopted to determine accurately the internal conversion coefficients of cascade transitions from angular correlation measurements. The method was applied to the 1064 keV - 570 keV cascade gamma rays in ^{207}Pb and 496 keV - 124 keV cascade gamma rays in ^{131}Cs. The values of α_K obtained for ^{207}Pb are:

$$(\alpha_K)_{570} = 0.016 \pm 0.001$$

$$(\alpha_K)_{1064} = 0.085 \pm 0.005$$

And those for ^{131}Cs are:

$$(\alpha_K)_{124} = 0.742 \pm 0.077$$

$$(\alpha_K)_{496} = 0.0100 \pm 0.0007$$

All these values except the one for the 124 keV transition in ^{131}Cs, are in excellent agreement with the theory. The ratio $\alpha_K(\text{exp})/\alpha_K(\text{theo})$ for 124 keV transition is 1.25 ± 0.13. This result is interpreted as being due to the presence of electric monopole, E0, electron transition and a strong case has been presented in support of this contention. A value of 0.26 ± 0.14 has been obtained for the E0/E2 electron conversion ratio and the absolute value of the electric monopole matrix element has been determined to be 0.07 ± 0.02.

Also measured were the K/L and K/(L + M) ratios of 570 keV, 1064 keV and 1770 keV transitions in ^{207}Pb. These are:

$(K/L)_{570} = 3.26 \pm 0.09$; $\{K/(L + M)\}_{570} = 2.71 \pm 0.08$

$(K/L)_{1064} = 3.64 \pm 0.10$; $\{K/(L + M)\}_{1064} = 3.07 \pm 0.09$

$\{K/(L + M)\}_{1770} = 4.70 \pm 0.13$

For the angular correlation measurements in ^{207}Pb the values obtained for correlation coefficients and particle parameters are:

	Electron-Gamma	Gamma-Electron
A_{22}	0.228 ± 0.027	0.161 ± 0.047
A_{44}	-0.074 ± 0.030	-0.041 ± 0.068
b_2	1.03 ± 0.12	0.68 ± 0.21

INTRODUCTION

Whenever a nucleus is formed in an excited state for which the excitation energy is insufficient for (nuclear) particle emission the dominant mode of dexcitation is by electromagnetic transitions. These transitions are of two main types:

(1) Emission of a gamma ray of energy k (in units of $m_ec^2 \approx 511$ ke' angular momentum L, for a pure multipole case.

(2) Internal conversion of an orbital electron with energy in continuum = $k - E_B$, angular momentum j_f = resultant of L and j_i. Here E_B is the binding energy and j_i the total angular momentum in the initial state.

The processes (1) and (2) are competitive with given initial and final states and the branching ratio of process (2) to (1) is called the internal conversion coefficient.

Figure 1 depicts in a diagramatic form the process in which a virtual photon is exchanged between a nucleus, initially in an excited state ψ_i and an electron initially in a bound state ϕ_i. After this exchange the nucleus and the electron

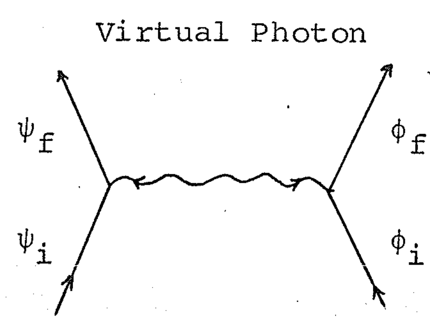


Figure 1

are in state ψ_f and ϕ_f respectively, ϕ_f being a continuum state. The transition probability for the process is given by

$$T_e \sim |< \psi_f \phi_f | H' | \psi_i \phi_i >|^2 \rho_e$$

as against the gamma emission probability

$$T_\gamma \sim |< \psi_f | H_\gamma | \psi_i >|^2$$

The ratio of the two as defined earlier is called the internal conversion coefficient, α.

INFORMATION OBTAINED FROM INTERNAL CONVERSION STUDY

The study of internal conversion process is of great importance in nuclear spectroscopy and can be used to gain information about the following:

(1) Nuclear spins

(2) Relative parities of nuclear levels

(3) Parameters such as nuclear matrix elements, the numerical value of which depend upon details of nuclear structure (for example, nuclear density functions, current density operators, etc.).

NEW IMPETUS

The first systematic calculations of internal conversion coefficients, based on the relativistic point nucleus, were made by Rose (1) and his coworkers. In general, these were in good agreement with the theory. In 1951 Sliv (2) pointed out that in some cases, particularly magnetic dipole transitions in heavy nuclei, the concept of point nucleus is not sufficient. Church and Weneser (3) showed that the introduction of the concept of a nucleus with finite size has two effects. First a "Static Effect" in which the electron wave functions are altered by finite size and second a "Dynamic Effect" arising from the penetration of atomic electrons into nuclear volume. The first correction being straight forward was made by Rose, Sliv and Band in subsequent calculations. The second term gives rise to new matrix elements for internal conversion coefficient, because of penetration of nuclear volume by atomic electrons which are different from ordinary conversion matrix elements (these are identical to gamma ray matrix elements). The effect is, naturally, most marked in cases of E0, M1 and E1 transitions. The most marked effect of the new internal conversion matrix is in cases of E0 mode of excitation. There is no corresponding E0 gamma ray and electric monopole transitions proceed solely by the penetration of finite nuclear volume by atomic electrons. It was also pointed out by Church and Weneser (3) that E0 can occur not just in $0^{+} \rightarrow 0^{+}$ transitions b also in competition with M1 and E2 transitions in cases where level spins and parities are the same.

In cases of M1 and E1 transitions, this effect is small and confined usually to heavy nuclei. For M1 Sliv defines a parameter $\lambda \sim \frac{M_e}{M_\gamma}$ where M_e is the new conversion matrix element, and M_γ the gamma ray matrix element. In most cases $\lambda \sim 1$. In some cases, however, when the gamma ray is retarded λ could be large and give an anomalous conversion coefficient.

The prospect of gaining new information about nuclear structure through conversion matrix elements arising from the penetration of nuclear volume by atomic electrons has given a new impetus to the study of internal conversion process.

INTERNAL CONVERSION THEORY

A detailed theory of internal conversion process has been worked out by Rose and is given elsewhere (5). The following is intended only to bring out some of the salient features that we have used in the present work.

The electron, initially in a bound state, interacts with the nucleus. The final state of the electron, as a result of this interaction, is such that the energy of the electron is in a continuum state. The angular momentum of the electron in the continuum state is specified by the quantum number

$$\kappa = \pm (j + \tfrac{1}{2})$$

where $$j = (\ell \mp \tfrac{1}{2})$$

If the initial state is a $S_{1/2}$ state, the final states of the electron for various values of j are given by

Transition	Initial State		Final States
E0 (No)	$S_{1/2}$	→	$S_{1/2}$ (= -1)
M1 (No)	$S_{1/2}$	→	$S_{1/2}$ (= -1)
		→	$d_{3/2}$ (= +2)
E1 (Yes)	$S_{1/2}$	→	$P_{1/2}$ (= +1)
		→	$P_{3/2}$ (= -2)
E2 (No)	$S_{1/2}$	→	$d_{3/2}$ (= +2)
		→	$d_{5/2}$ (= -3)

and so on.

The theoretical expression for K-conversion coefficient is

$$\alpha_K^{(\tau L)} = \sum_{\kappa} |M_{\kappa}^{(\tau L)}|^2 \qquad (1)$$

where τ = type of radiation

L = multipolarity of the radiation

K = atomic shell or subshell

κ = defines the state of the free electron

The conversion electron matrix element given by (1) is composed of two parts, one of which is real and the other imaginary.

$$\sum_{\kappa} |M_{\kappa}^{(\tau \ell)}|^2 = \sum_{\kappa} |\mathrm{Re}M_{\kappa} + 1\ \mathrm{Imag.}\ M_{\kappa}|^2$$

Equation (1) is valid for a pure multipole transition. If the transition is mixed then α(total) can be written as

$$\alpha = \frac{\alpha(ML) + \delta^2 \alpha(EL')}{1 + \delta^2}$$

where δ^2 is called the mixing ratio, and is defined by

$$\delta^2 = \frac{\text{number of L' pole gamma rays}}{\text{number of L- pole gamma rays}}$$

No mention has so far been made of the size of the nucleus. As stated earlier the size of the nucleus has two effects on the conversion coefficient called the 'static' and the 'dynamic' effects. Corrections for the "static effect" are straightforward to apply. The "dynamic effect", however, is more complicated. When this effect is taken into account, a new matrix element for internal conversion is obtained. This matrix element has two parts and can be written as

$$B_K^e = O_K + N_K$$

The first part corresponds to the conversion matrix element arising from the interaction of the nucleus and electron in the region outside the nucleus. The second one is related to the penetration matrix element due to interaction between the electron and the nucleus inside the nuclear volume. The ratio of the matrix N_K to N_γ is a measure of the penetration effects and is called λ. For an M1 transition the penetration is usually small and $\lambda \sim 1$. When $\lambda \neq 1$ the conversion coefficient is given by

$$\beta_K(\lambda) \sim \beta_K(\lambda = 1) \left[1 - (\lambda - 1)\ C(Z,k)\right]^2$$

ROLE OF ANGULAR CORRELATION

If a conversion transition appears in the decay scheme as a branch of a cascade as in figure 2, angular correlation measurements can be very useful in determining the values of δ^2, the mixing ratio and λ the matrix element ratio.

The probability that an electron e_1 of the first transition be observed at an angle θ with respect to a gamma ray of the second transition is given by

$$W(\theta) = 1 + A_{22}P_2(\cos\theta) + A_{44}P_4(\cos\theta)$$

where A_{22} and A_{44} are called the correlation coefficients. The coefficients A_{22} and A_{44} are given by

$$\left.\begin{aligned} A_{22}(e_1\gamma_2) &= F_2(e_1)\ F_2(\gamma_2) = b_2(e_1)\ F_2(\gamma_1)\ F_2(\gamma_2) \\ A_{44}(e_1\gamma_2) &= F_4(e_1)\ F_4(\gamma_2) = b_4(e_1)\ F_4(\gamma_1)\ F_4(\gamma_2) \end{aligned}\right\} \quad (2)$$

The F's are functions of spins and multipolarities. The b's are called particle parameters and are functions of the radial matrix elements and hence very sensitive to nuclear structure effects.

Similar expressions can be written for the γ_1-e_2 angular correlation case. If the transitions are not pure but have a mixing ratio δ^2, as defined earlier, a slightly more complicated expression results.

It is clear from equation (2) that from a knowledge of the correlation coefficients we can determine particle parameters which are extremely sensitive to nuclear structure effects and would be very helpful in obtaining information about the structure of the nucleus.

A NEW APPROACH

A new approach has been adopted to determine accurately the internal conversion coefficients of cascade transitions from angular correlation measurements. In this method we measure either the electron-gamma or the gamma-electron angular correlation of the cascade transitions and not both as is usually done. The internal conversion coefficients so determined are independent of the angular correlation function, W(θ), so that they are not affected even when the angular correlation is perturbed or the coefficient A_{44} of the angular correlation function is too large to be neglected. Also the errors of the conversion coefficients are not affected by the rather usual large error of the angular correlation coefficients.

Referring to figure 2, let N_o be the population of the level of the parent nucleus and x and y the relative number of transitions as shown. Then the population of the upper and the intermediate levels of the daughter nucleus are respectively,

$$xN_o \text{ and } yN_o.$$

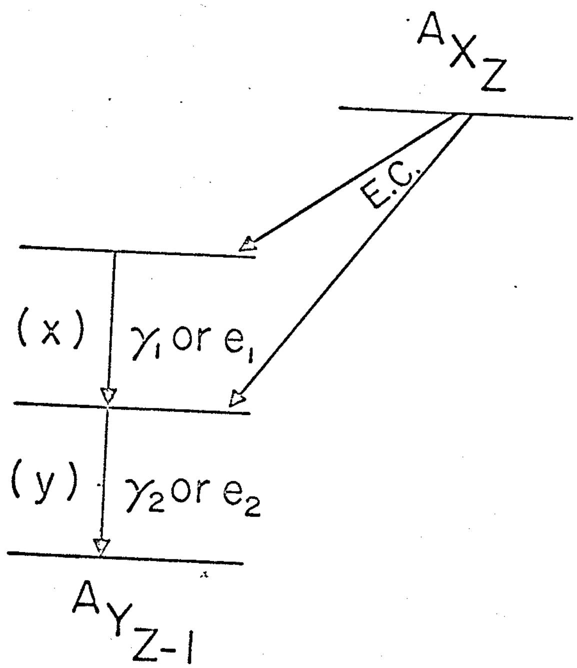
The number of K-electrons in the first transition is,

$$N_K^{e_1} = \alpha_1^K \; N_{\gamma_1} = \alpha_1^K \; \frac{xN_o}{1 + \alpha_1^T}$$

For each K-electron in first transition there is $\frac{1}{1 + \alpha_2^T}$ gamma ray in the second transition. The probability of detecting a K-electron (of the first transition) in the peak $= \varepsilon_{e_1}^p \; \omega_{e_1}$.

FIGURE 2

Simple Nuclear Cascade



AX Z
E.C.
(x)
γ1 or e1
(y)
γ2 or e2
AY Z-1

The probablity of detecting in the peak a gamma ray (of the second transition) which is related to this K-electron of the first transition, $= \varepsilon^{p}_{\gamma_2} \omega_{\gamma_2}$.

The probability that a gamma ray in the second transition related to the K-electron in the first transition will go to the gamma ray detector placed at an angle θ with respect to the electron detector, when the K-electron went to the electron detector, $= \varepsilon^{K}_{e_1-\gamma_2} W_1(\theta)$ where $\varepsilon^{K}_{e_1-\gamma_2}$ is the coincidence efficiency and $W(\theta)$ the angular correlation function. Hence for xN_o transitions, the number of $e^{K}_1 - \gamma_2$ coincidence events is,

$$C_1(\theta) = C_{e^K_1-\gamma_2}(\theta) = \left[\frac{xN_o}{1+\alpha^T_1} \alpha^K_1 \varepsilon^p_{e_1} \omega_{e_1}\right] \left[\frac{1}{1+\alpha^T_2} \varepsilon^p_{\gamma_2} \omega_{\gamma_2}\right]$$

$$\times \left[\varepsilon^{K}_{e_1-\gamma_2} \overline{W}_1(\theta)\right] \qquad (3)$$

where $\overline{W}_1(\theta) = \int W_1(\theta) \quad \varepsilon^{p}(\beta) \, d\Omega$

For the γ_2 singles peak,

$$A_{\gamma_2} = N_{\gamma_2} \varepsilon^{p}_{\gamma_2} \omega_{\gamma_2}$$

$$= \frac{yN_o}{1+\alpha^T_2} \varepsilon^{p}_{\gamma_2} \omega_{\gamma_2} \qquad (4)$$

Hence,

$$\frac{C_1(\theta)}{A_{\gamma_2'}} = \left[\frac{xN_o}{1+\alpha_1^T}\ \alpha_1^K\ \varepsilon_{e_1}^K\ \omega_{e_1}\right]\left[\frac{1}{1+\alpha_2^T}\ \varepsilon^p_{\gamma_2'}\ \omega_{\gamma_2}\right]\left[\varepsilon^K_{e_1-\gamma_2'}\ \overline{W}_1(\theta)\right] \times \left[\frac{1+\alpha_2^T}{yN_o\varepsilon^p_{\gamma_2'}\omega_{\gamma_2'}}\right]$$

$$= \frac{x}{y}\cdot\frac{\alpha_1^K}{1+\alpha_1^T}\cdot\varepsilon_{e_1}^K\omega_{e_1}\ \varepsilon^K_{e_1-\gamma_2}\ \omega_{\gamma_2}\ \overline{W}_1(\theta) \qquad (5)$$

which is an expression for the coincidence (normalised to singles counts of the movable detector) between the K-electrons of the first transition and the gamma rays of the second transition.

In this expression x/y is the ratio of the number of the first transition to that of the second transition, $\varepsilon^K_{e_1-\gamma_2}$ the coincidence efficiency, ω_{e_1} is the solid angle for the electrons, $\varepsilon^K_{e_1}$ is the detection efficiency for the K-electrons, α_K and α_T are the K-conversion and the total conversion coefficient respectively and $A_{\gamma_2'}$ is the area under that part of the gamma spectrum which is accepted by the detector at the angle θ.

Similarly we can write for the coincidence between the gamma ray of the first transition and the K-electron of the second transition as,

$$\frac{C_2(\theta)}{A_{\gamma_1'}} = \frac{\alpha_2^K}{1+\alpha_2^T}\ \varepsilon^K_{\gamma_1-e_2}\ \overline{W}_2(\theta)\ \omega_{e_2}\ \varepsilon^K_{e_2} \qquad (6)$$

Now we express the experimentally determined normalised coincidence counts in terms of Lengendre Polynomial Series,

$$C(\theta) = a_o + a_2P_2 (\cos\theta) + a_4P_4 (\cos\theta) \quad (7)$$

so that $$\overline{W}(\theta) = \frac{C(\theta)}{a_o} \quad (8)$$

$$= 1 + A_{22}P_2 (\cos\theta) + A_{44}P_4 (\cos\theta) \quad (9)$$

Combining equations (5) and (8) and writing

$\alpha_1^T = \alpha_1^K \left[1 + \frac{L + M}{K}\right]$ we get,

$$\frac{\alpha_1^K}{1 + \alpha_1^K \left[1 + \frac{L + M}{K}\right]} = \frac{a_o}{A_{\gamma_2}} \; \frac{y}{x} \; \frac{1}{\varepsilon^K_{e_1-\gamma_2}} \; \frac{1}{\varepsilon^K_{e_1}\omega_{e_1}} \quad (10)$$

where a_o is found by measuring the electron-gamma angular correlation at three angles and using (8).

Similarly, for the gamma-electron angular correlation

$$\frac{\alpha_2^K}{1 + \alpha_2^K \left[1 + \frac{L + M}{K}\right]} = \frac{a_o'}{A_{\gamma_1}} \; \frac{1}{\varepsilon^K_{\gamma_1-e_2}} \; \varepsilon^K_{e_2}\omega_{e_2} \quad (11)$$

From the singles spectra of the conversion electron we find K/(L + M) ratios and thus calculate the value of K-conversion coefficients.

The numbers of transitions are given by

$$x = N_{\gamma_1}\left(1 + \alpha_1^T\right) = \frac{A_{e_1}^K}{\varepsilon_{e_1}^K \omega_{e_1}} \cdot \frac{1 + \alpha_1^T}{\alpha_1^K} \tag{12}$$

and

$$y = N_{\gamma}\left(1 + \alpha_2^T\right) = \frac{A_{e_2}^K}{\varepsilon_{e_2}^K \omega_{e_2}} \cdot \frac{1 + \alpha_2^T}{\alpha_2^K} \tag{13}$$

Here A_e^K are the areas under the conversion electron peaks of the singles spectrum. Thus from (10), (11), (12) and (13) we obtain

$$\left(\frac{A_{e_1}^K}{A_{e_2}^K}\right)\left(\frac{a_o'}{A_{\gamma_1}}\right)\left(\frac{A_{\gamma_2}}{a_o}\right)\left(\frac{\varepsilon_{e_1\gamma_2}}{\varepsilon_{\gamma_1 e_2}}\right) = 1 \tag{14}$$

Equation (14) enables us to eliminate one of the angular correlation measurements. Suppose we measure the electron-gamma angular correlation. This yields the value of $\frac{a_o}{A_{\gamma_2}}$ which when substituted in (14) yields the value of $\frac{a_o'}{A_{\gamma_1}}$ to be used in (11) for the determination of α_2^K. Thus, to determine α_1^K and α_2^K in cascade transitions we require the measurement of either electron-gamma or gamma-electron angular correlation and not both as is usually done.

We can write for the gamma ray intensity

$$N_\gamma = \frac{N_K^e}{\alpha_K} = \frac{A_K^e}{\varepsilon_K^e \ \omega_e \ \alpha_K} \qquad (15)$$

So that if the electron detection efficiencies are assumed to be the same at both energies then the relative gamma ray intensity is given by

$$\frac{N_{\gamma_1}}{N_{\gamma_2}} = \frac{A_{e_1}^K}{A_{e_2}^K} \quad \frac{\alpha_2^K}{\alpha_1^K} \qquad (16)$$

The areas can be measured from the electron singles spectrum and the relative gamma ray intensity can be computed using equation (16).

APPARATUS

DETECTORS

The electron detector used in the experiment was a Si(Li) solid state detector obtained from SIMTEC.[a] Its active area is 50 mm^2. The depletion depth at a bias of 1000 volts is 3 mm which corresponds to the range of a 2 MeV electron in silicon. For singles counts, the pulses from the solid state detector were led through the low noise Nuclear Enterprises[b] 5231 preamplifier and were further amplified by a Nuclear Enterprises 5230 RC amplifier. In the coincidence work the output pulse from the preamplifier was also fed simultaneously into an ORTEC[c] 203 amplifier which produces double delay line clipped pulses necessary to drive a crossover pick off unit. The detector is cooled to liquid nitrogen temperature. At this temperature the resolution obtained for the system is 6.5 keV for the 1064 keV transition.

For the gamma ray singles spectrum of ^{207}Pb a Ge(Li) solid state detector was used. The detector has an active area of 2.78 cm^2 and a 2 mm depletion depth and was obtained from RCA[d]. The pulses from the detector were amplified using a Tennelec[e] TC 200 amplifier. The system was capable of a resolution of 6 keV at 1064 keV.

(a) Simtec Ltd., Montreal
(b) Nuclear Enterprises Ltd., Winnipeg
(c) Oakridge Technical Enterprises Corp., Oak Ridge, Tennessee
(d) RCA, Montreal
(e) Tennelec, Oak Ridge, Tennessee

In the case of the angular correlation work a 1 1/2" × 1" NaI(Tℓ) crystal mounted in an integral line assembly with a Dumont 6292 photomultiplier tube was used for the detection of gamma rays. Pulses from this unit were fed, through the cathode follower, to a Nuclear Enterprises 5202 double delay line amplifier.

ELECTRONICS

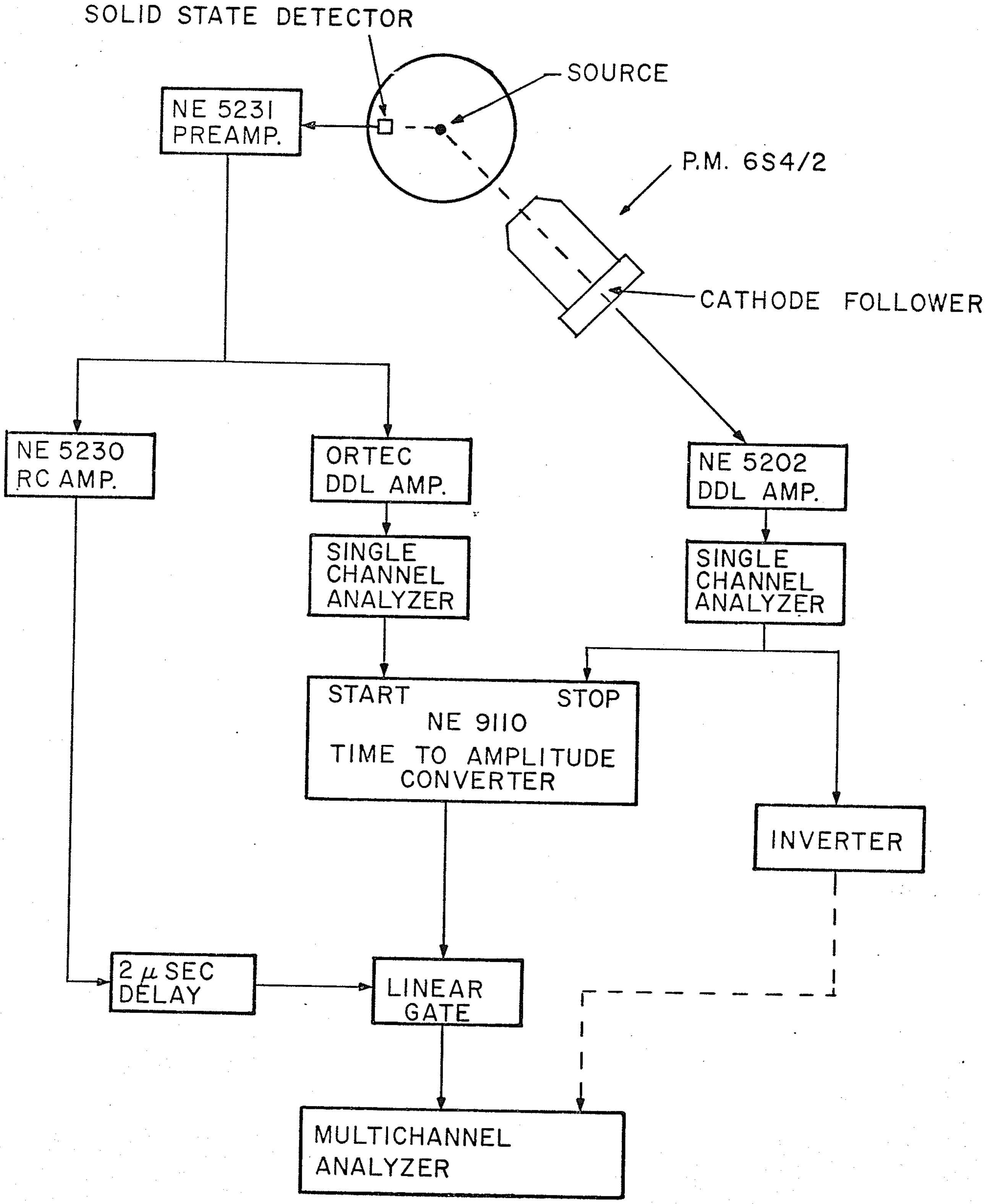
The block diagram for the electronics is given in figure 3. The function of the apparatus was to select those pulses of the correct energy from the detector which were in coincidence with a detected gamma ray, also of correct energy. The electron pulses were then analysed in a Nuclear Data 1024 channel analyser and from this data, the angular correlation function was obtained.

After amplifying, the pulses obtained from the electron and gamma ray detectors, are fed into two single channel analysers. The windows of the single channel analysers are set to accept the appropriate electron and gamma ray energies. The output pulses from the single channel analysers, which are initiated at the crossover point of the double delay line pulses, are fed into a time to amplitude converter (TAC) type fast coincidence system. The (TAC) gives out pulses whose amplitude is proportional to the time difference between the two input pulses.

FIGURE 3

Schematic Block Diagram

Schematic Block Diagram



The output pulses from the (TAC) are fed through a single channel analyser which accepts only those pulses which have the correct amplitude, corresponding to coincidence events. The output pulses from the TAC are used to gate the 1024 channel analyser which analyses the electron pulses from the good resolution RC amplifier. After a coincidence spectrum had been taken, the single channel analyser output was used to obtain gated gamma ray singles spectrum. The singles count rate of the movable detector was used to normalize the coincidence counting rate at each angle. This is to correct for the finite size of the source and for the possibility of the source not being in the exact centre of the arc described by the gamma ray counter.

EXPERIMENTAL CHAMBER

The experimental chamber is so constructed that it has cylindrical symmetry about the axis of rotation of the movable detector. The aluminum planchette source rings were held vertically in the centre of the vacuum chamber 2.7 cm from the solid state electron detector. The chamber was evacuated by a Balzer's rotary pump. A liquid nitrogen cold trap was used to keep the oil vapours from entering the chamber containing the source and the detector.

For more details about the chamber and the cooling arrangement the reader is referred to Dohan's thesis (6).

SOURCES

For a study of this kind it is desirable that the source decay by 100% electron capture so that there would not be any background beta radiation. The presence of this radiation would make the subtraction of background extremely difficult.

The source chosen was ^{207}Bi. It has a half life of 28 years and decays by electron capture to excited states of ^{207}Pb. The source is well known and is used as a calibration standard. It was obtained from ORTEC as isotopically separated atoms firmly deposited on 0.0005" plastic to minimize scattering and had a strength of 1 microcurie. For the ^{131}Cs source, the reader's attention is once again drawn to Dohan's thesis (6).

RESULTS ON ^{207}Pb

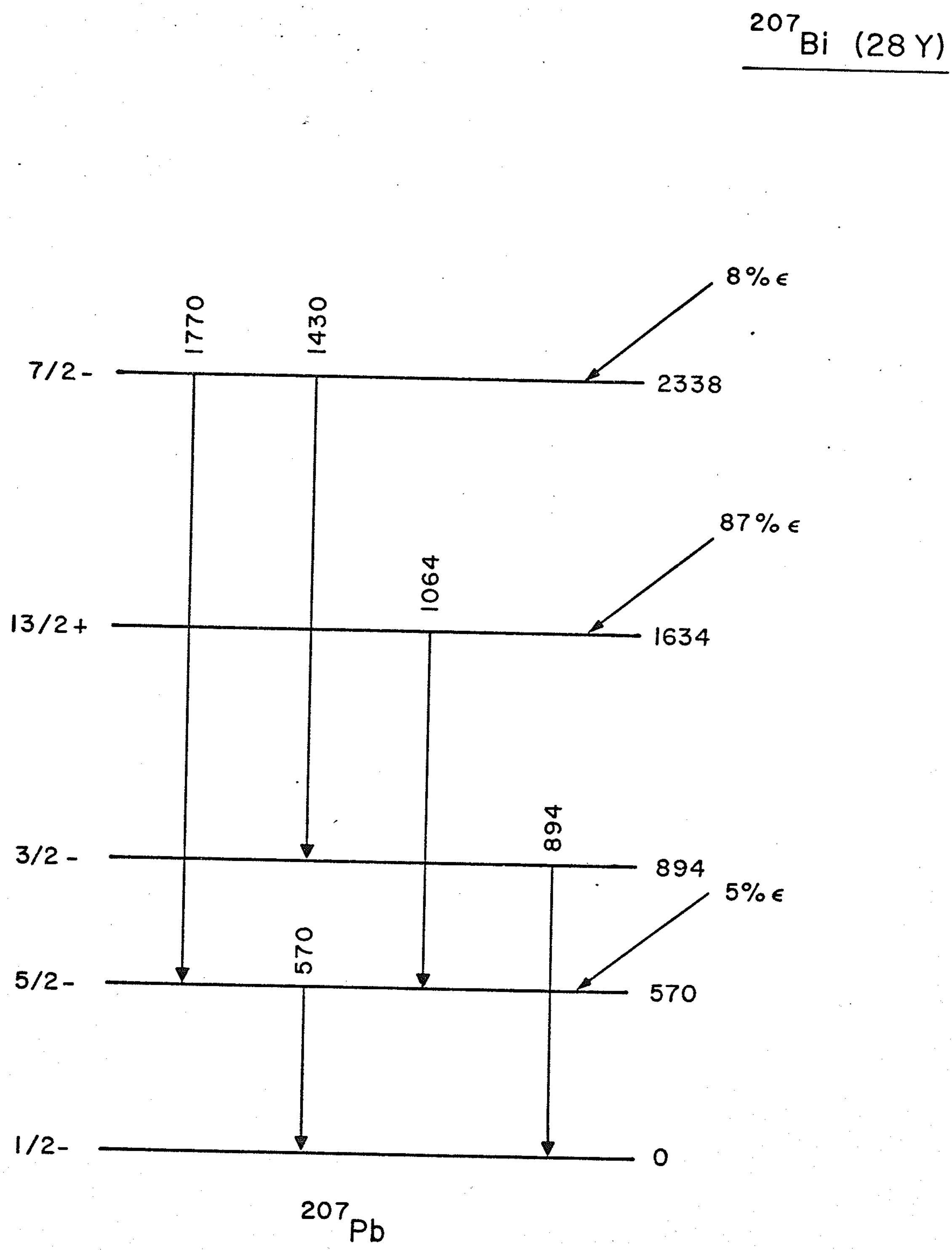
The currently accepted energy level scheme for ^{207}Pb is given in figure 4. The 570 keV, 1064 keV and 1770 keV transitions were investigated.

The gamma ray singles spectrum is shown in figure 5. A resolution of 6 keV at 1064 keV was obtained for the system.

The electron singles spectrum is shown in figure 6. The spectrum was taken with a Si(Li) solid state detector cooled to liquid nitrogen temperature. The applied bias of 1000 volts corresponds to the range of 2 Mev electron in silicon. The K/L and K/(L + M) ratios shown in table 1 were obtained from this spectrum. The theoretical values of the K/L ratios were obtained by graphical interpolation of the internal conversion coefficients calculated by Sliv and Band (7), assuming a pure E2 assignment for 570 keV transition and a pure M4 assignment for 1064 keV transition. For the 1770 keV gamma ray we used the reported (8) admixture; 97% E2 and 3% M3 which is consistent with that measured by Alburger and Sunyar (9). Our values of 3.26 ± 0.09 and 3.64 ± 0.10 for K/L ratio of 570 keV and 1064 keV transitions respectively are in good agreement with measurements of Alburger and Sunyar (9). Our K/(L + M) ratios, however, do not agree with those of Kurey and Roy (10), who we believe encountered some difficulties

FIGURE 4

Energy Level Scheme of ^{207}Pb



^{207}Bi (28 Y)
8% ϵ
87% ϵ
5% ϵ
1770
1430
1064
894
570
7/2-
13/2+
3/2-
5/2-
1/2-
2338
1634
894
570
0
^{207}Pb

FIGURE 5

Gamma Ray Singles Spectrum of ^{207}Pb

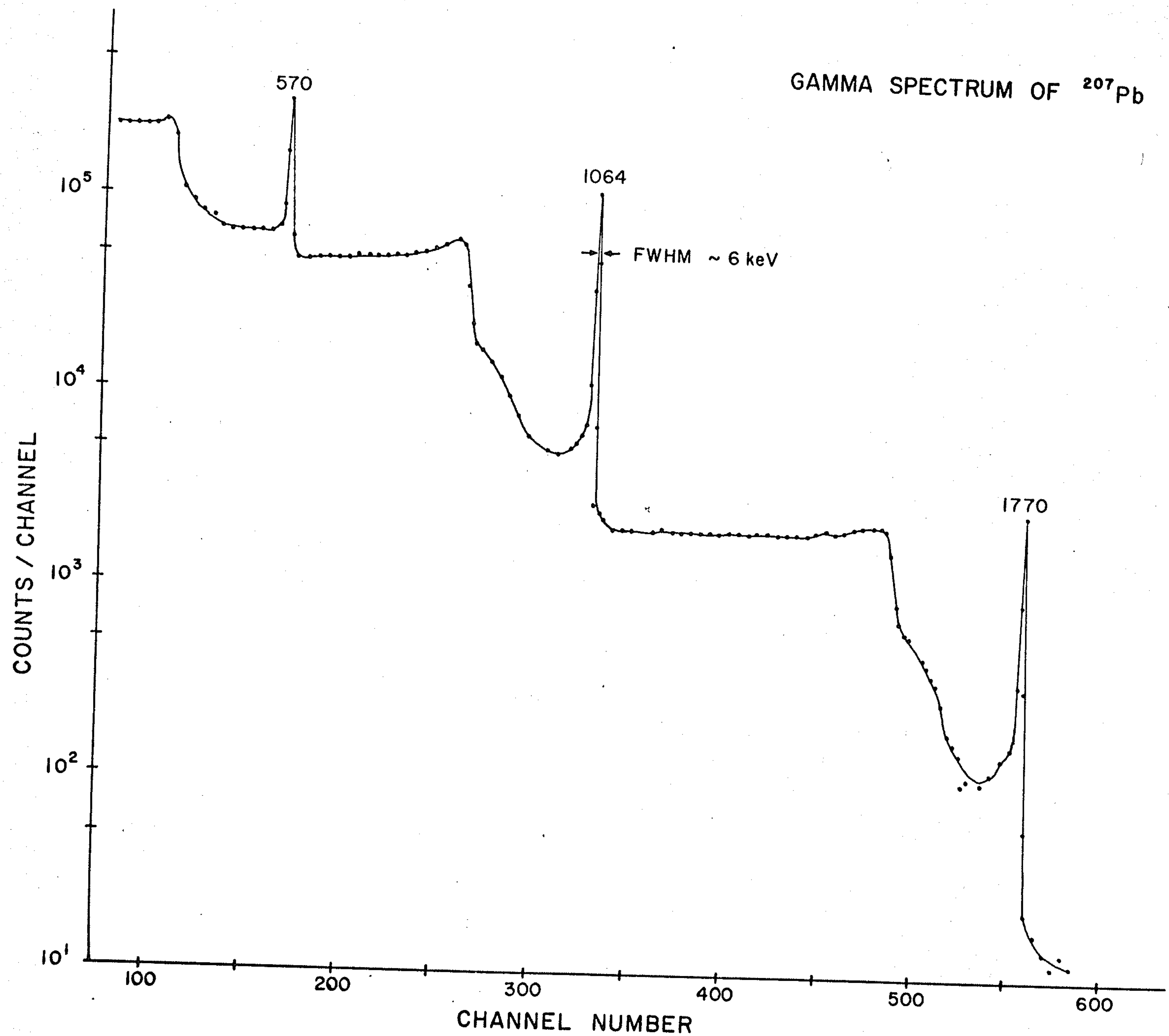
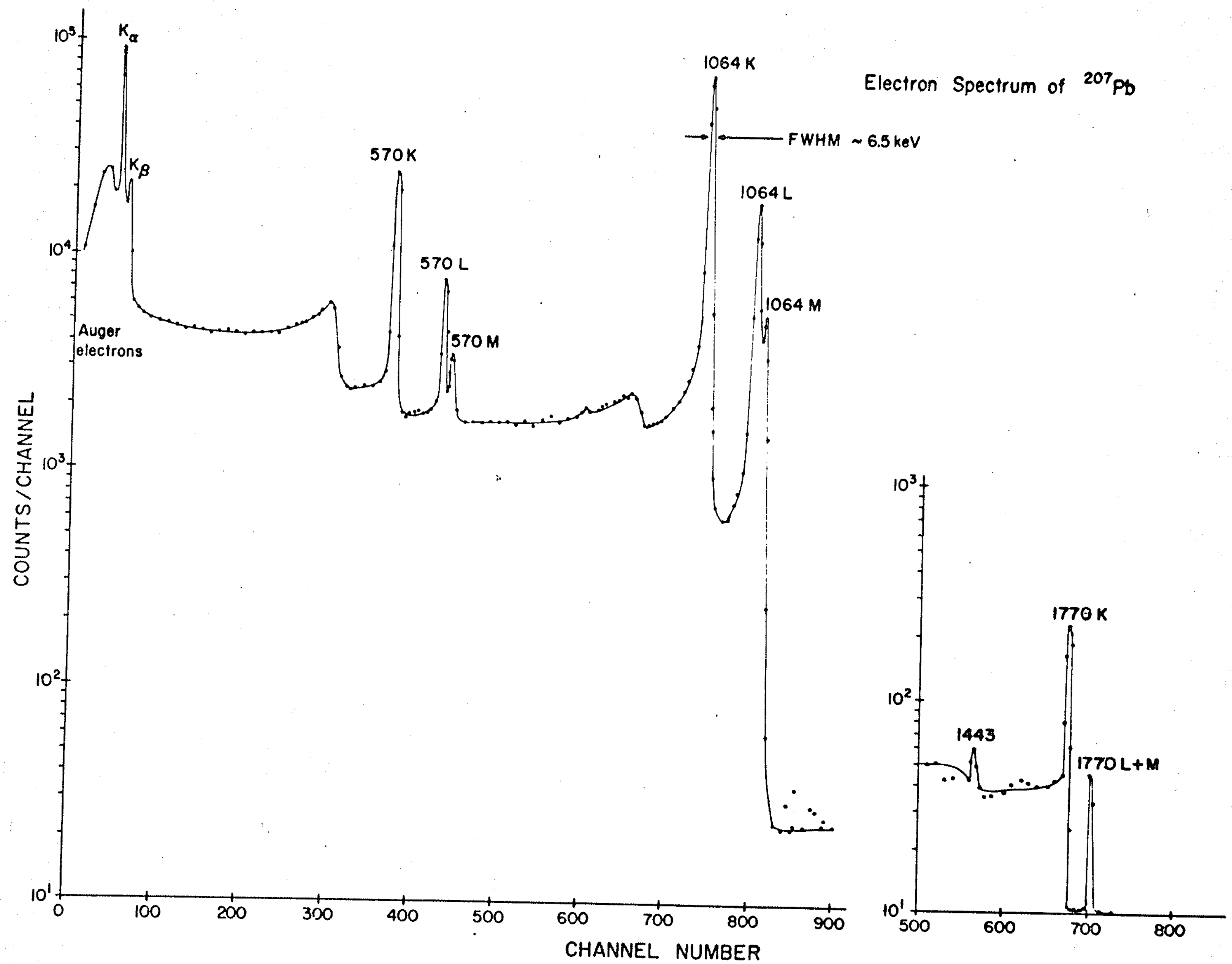

GAMMA SPECTRUM OF ^{207}Pb
570
1064
FWHM ~ 6 keV
1770
COUNTS / CHANNEL
10^5
10^4
10^3
10^2
10^1
100
200
300
400
500
600
CHANNEL NUMBER

FIGURE 6

Conversion Electron Singles Spectrum of ^{207}Pb



Electron Spectrum of ^{207}Pb
COUNTS/CHANNEL
CHANNEL NUMBER
K_α
K_β
Auger electrons
570 K
570 L
570 M
1064 K
1064 L
1064 M
FWHM ~ 6.5 keV
1443
1770 K
1770 L+M

TABLE 1

K/L and K/(L + M) Ratios in ^{207}Pb

Ratio	Alburger and Sunyar	Kurey and Roy	Present Work	Theory
$(K/L)_{570}$	3.4 ± 0.4	-	3.26 ± 0.09	3.44 (E2)
$(K/L)_{1064}$	3.95 ± 0.25	-	3.64 ± 0.10	3.76 (M4)
$(K/L + M)_{570}$	-	3.11 ± 0.11	2.71 ± 0.08	-
$(K/L + M)_{1064}$	-	4.34 ± 0.17	3.07 ± 0.09	-
$(K/L + M)_{1770}$	-	-	4.70 ± 0.13	-

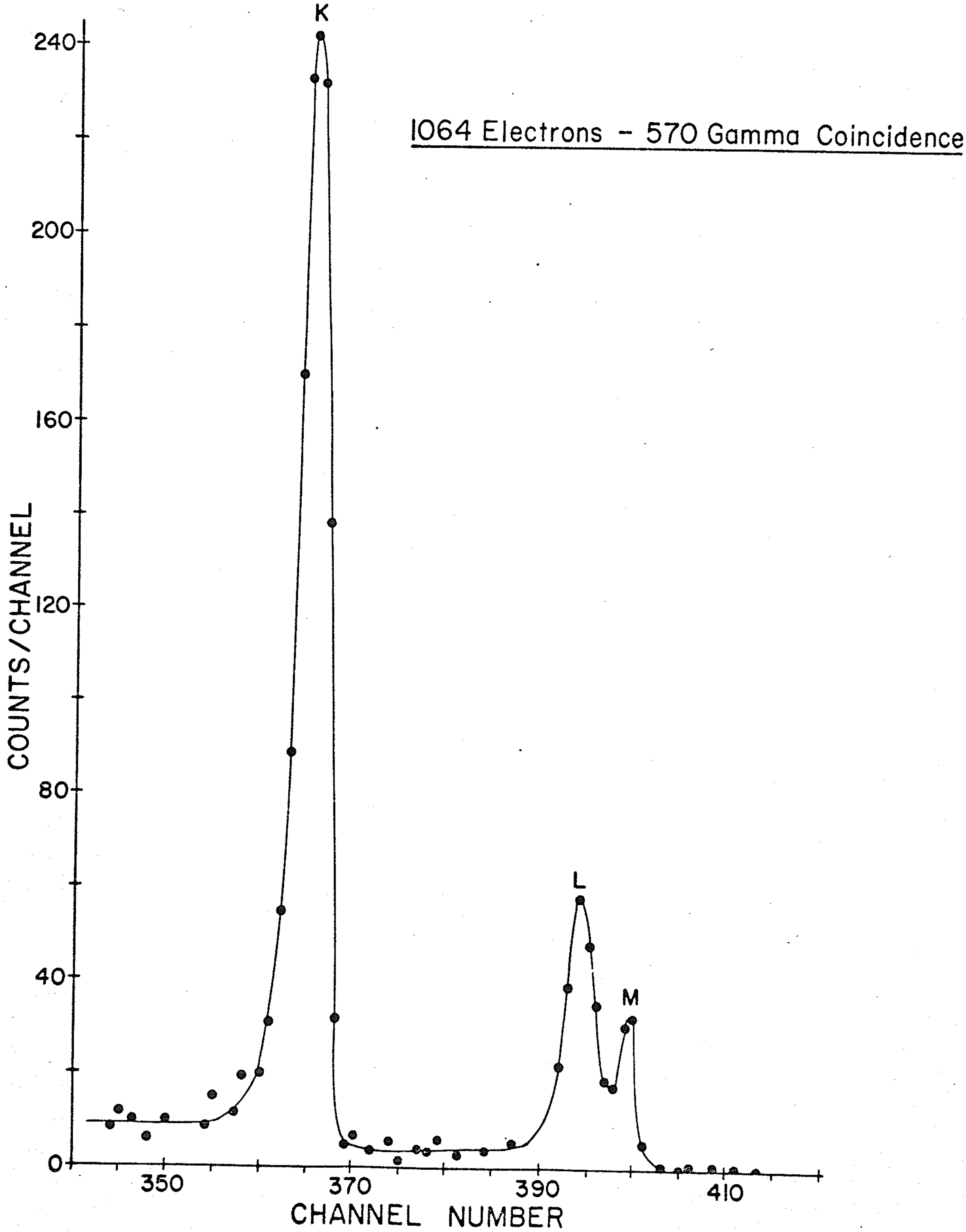
concerning the depletion depth of the detector. Comparison of data with theoretical values of the internal conversion coefficient ratios indicates good agreement with the E2 assignment for the 570 keV transition and M4 assignment for the 1064 keV transition. The errors in the values of conversion coefficient ratios accumulate from the measurements of relative areas of the electron singles spectrum.

ANGULAR CORRELATION EXPERIMENT

For the first part of the angular correlation experiment the windows of the single channel analyzer were set in such a way as to accept the 570 keV gamma rays and 1064 keV electrons. The (TAC) discriminators were set to accept the coincidences between the selected pulses. Coincidences were taken for a ten hour period at each of the angles 90^{0}, 135^{0} and 180^{0} between the fixed detector and the movable detector (gamma ray detector in the present case). These angles were scanned twice alternately in opposite directions. A gated singles gamma ray spectrum was taken at each angle after the experiment. In the second part of the experiment the same procedure was repeated but this time the single channel analyzer was set to accept the 570 electrons and 1064 gamma rays. A typical coincidence gated electron spectrum with an angle of 180^{0} between the detectors is shown in figure 7. The total number of coincidences were found at each angle by subtracting the back scattered contribution from the (L + M) electrons and insisting that the peaks be symmetrical. The coincidence counting

FIGURE 7

Conversion Electron Coincidence Spectrum of ^{207}Pb



1064 Electrons - 570 Gamma Coincidence
K
L
M
COUNTS/CHANNEL
CHANNEL NUMBER
240
200
160
120
80
40
0
350
370
390
410

rate was then normalized to the corresponding gamma ray singles rate. The quantity $W(\theta)/W(90)$ was plotted as a function of angle θ between the two detectors and is shown in figures 8 and 9. The errors indicated in each figure are the statistical errors in counts at each point.

ANALYSIS OF DATA

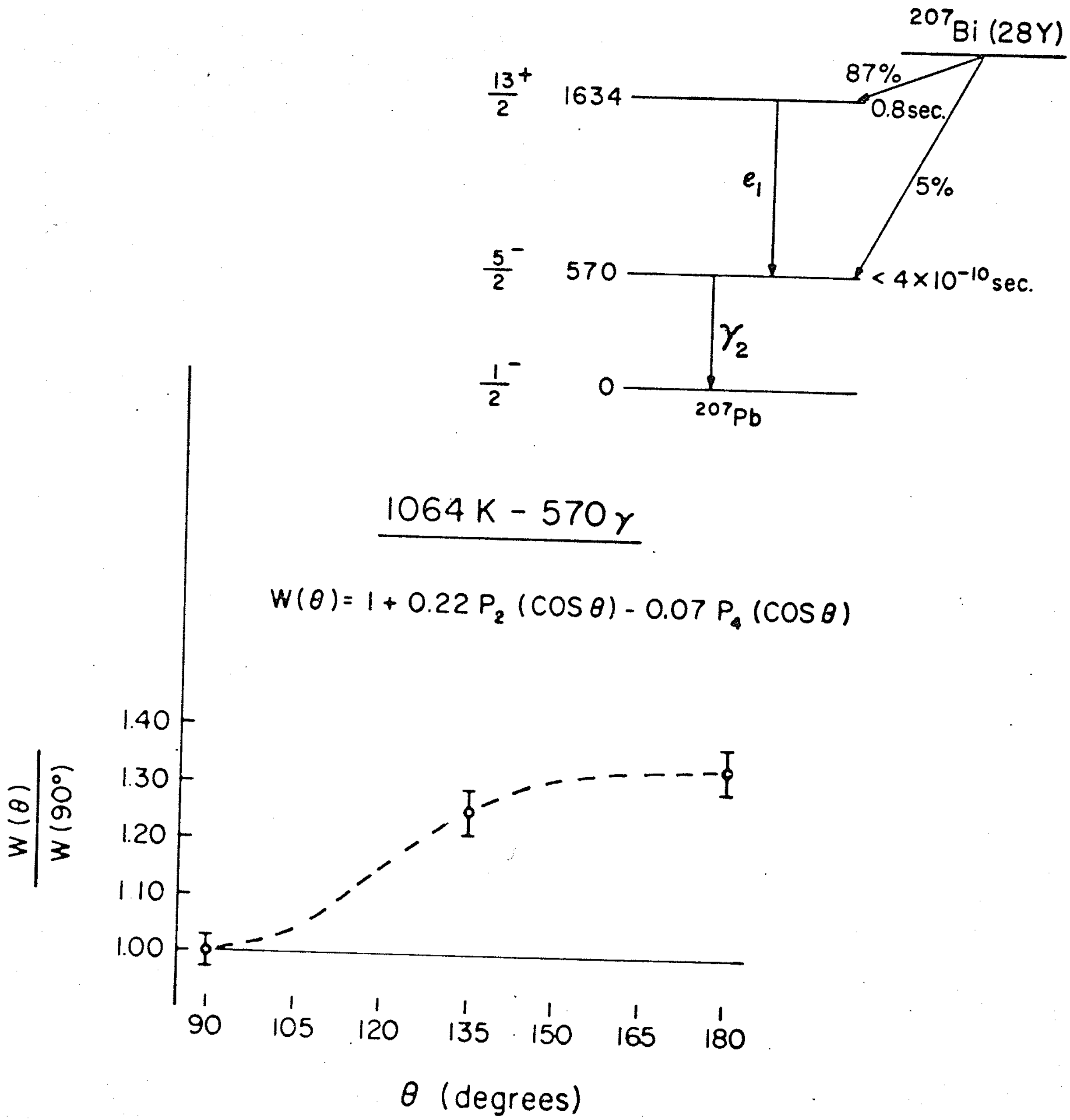
For the analysis of the data White's (11) method was used. In this method it has been shown that it is sufficient to take data at $\frac{m}{2} + 1$ angles where m is the highest order Legendre Polynomial in the expansion of $W(\theta)$. For $m = 4$, as in the present case, it is shown that to maximise the efficiency of statistics, the data should be taken at angles of 90^{o}, 135^{o} and 180^{o}. The experimentally obtained quantities $W(\theta_i)$ at the above mentioned three angles were used to solve the system of equations,

$$W(\theta_i) = 1 + A_{22}P_2(\cos\theta_i) + A_{44}P_4(\cos\theta_i) \quad i = 1, 2, 3.$$

The coefficients so obtained were corrected for finite solid angle using Yates tables (12). These corrections are introduced to account for the 'smearing out' produced by the finite size of the detector. The calculation of this smearing out can be extremely difficult but is considerably simplified if all detectors have cylinderical symmetry. These values of the

FIGURE 8

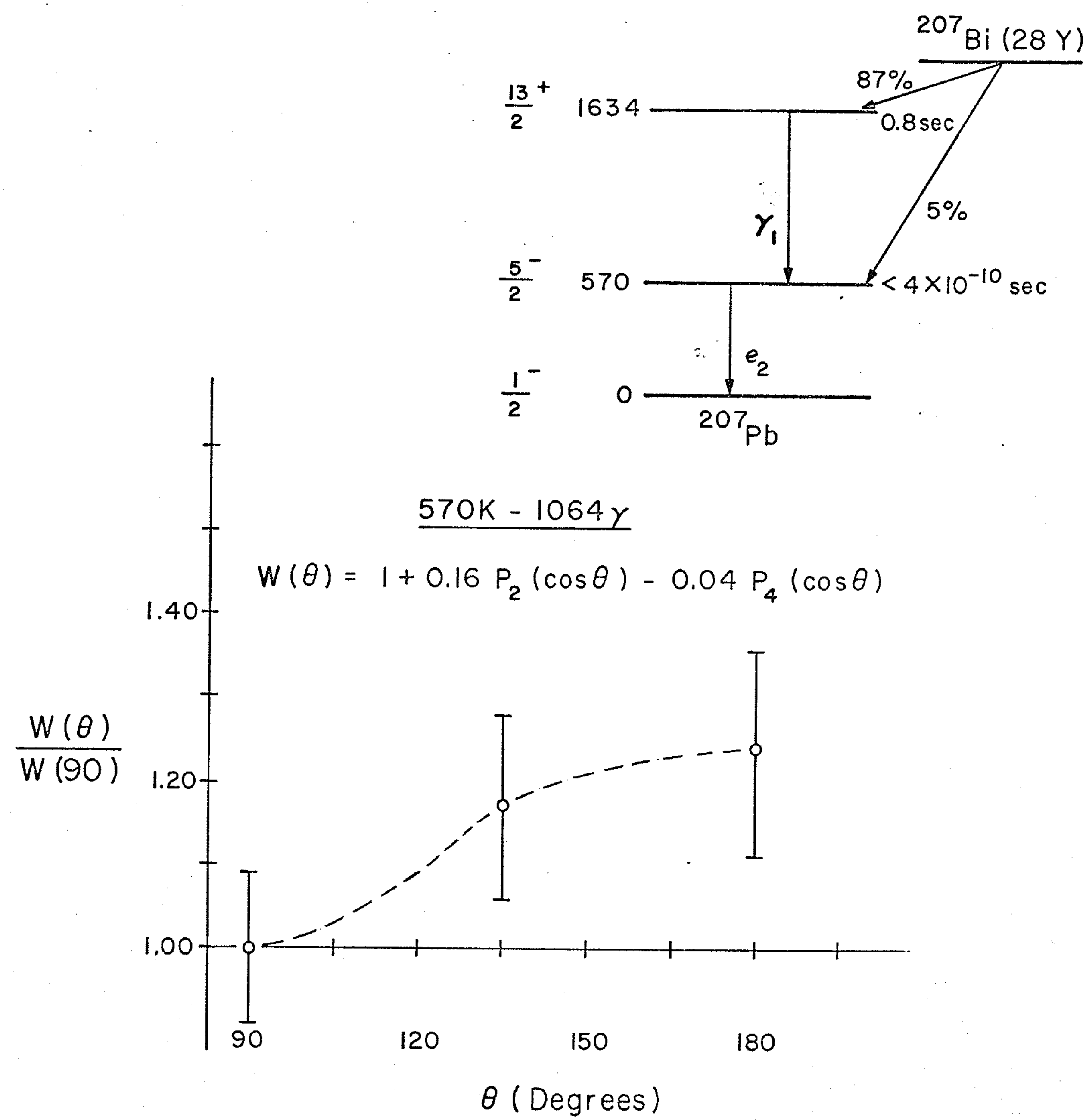
$W(\theta)/W(90)$ Vs θ (1064K - 570γ)



207Bi (28Y)
87%
0.8 sec.
5%
13/2 +
1634
e1
5/2 −
570
< 4×10⁻¹⁰ sec.
γ2
1/2 −
0
207Pb
1064 K - 570 γ
W(θ) = 1 + 0.22 P2 (COS θ) - 0.07 P4 (COS θ)
W(θ)/W(90°)
1.40
1.30
1.20
1.10
1.00
90
105
120
135
150
165
180
θ (degrees)

FIGURE 9

$W(\theta)/W(90)$ Vs θ (1064 γ-570K)



^{207}Bi (28 Y)
87%
5%
13/2 + 1634
0.8 sec
γ_1
5/2 − 570
< 4×10^{-10} sec
e_2
1/2 − 0
^{207}Pb
570K - 1064γ
$W(\theta) = 1 + 0.16\, P_2(\cos\theta) - 0.04\, P_4(\cos\theta)$
W(θ) / W(90)
1.40
1.20
1.00
90
120
150
180
θ (Degrees)

correlation coefficients were used to determine the partial parameter from the relations (for pure multipoles),

$$A_{22}\ (e_1\gamma_2) = b_2^m\ F_2^m\ (\gamma_1)\quad F_2^e(\gamma_2)$$

$$A_{22}\ (\gamma_1 e_2) = b_2^e\ F_2^e\ (\gamma_2)\quad F_2^m(\gamma_1)$$

where b's are particle parameters and F's are functions of spins and multipolarities. Particle parameters are functions of quantities on which internal conversion depends and can thus be considered as a measure of the strength of internal conversion process. They are very sensitive to nuclear structure effects. The angular correlation coefficients are given in table 2 and the particle parameters in table 3. The theoretical values are also given for comparison.

Equations (10) and (11) were used to determine the values of K-conversion coefficients. In the present case the coincidence efficiencies $\varepsilon_{e_1\gamma_2}$ and $\varepsilon_{\gamma_1 e_2}$ are unity. The efficiences for detection of electrons at 570 keV and 1064 keV are assumed to be unity while the solid angle for the electrons was determined accurately. For the ratio, $\frac{x}{y}$, the adopted values given in Nuclear Data Sheets (13) were used. The analyzed experimental data are displayed in table 4. Table 5 gives relative gamma ray intensities obtained from internal conversion coefficients. The errors quoted include

TABLE 2

Angular Correlation Coefficients

Transition Energy (keV)	A_{22}	A_{44}
1064	$+ 0.228 \pm 0.027$	$- 0.074 \pm 0.030$
570	$+ 0.161 \pm 0.047$	$- 0.041 \pm 0.068$

TABLE 3

Particle Parameters

Transition Energy (keV)	b_2 exp.	b_2 theor.
1064	1.03 ± 0.12	1.04 (M4)
570	0.68 ± 0.21	1.21 (E2)

TABLE 4

K-Conversion Coefficients

Transition Energy (keV)	Kleinheinz et al	Theory	Present Work
570	0.016	0.016 (E2)	0.016 ± 0.001
1064	0.009	0.094 (M4)	0.085 ± 0.005

those of the measurements of areas, the x/y ratio, solid angle and the K/(L + M) ratio.

DISCUSSION OF RESULTS

As can be seen in table 4, the measured values of α_K are in good agreement with the theoretical values of Sliv and Band (7) and also with the recent measurements of Kleinheinz et al (14). Table 5 gives the values of gamma ray intensities from our measurements and using equation (16). To determine the relative gamma ray intensity of the 1770 keV transition, we used for α_K of the 1770 keV transition the theoretical value of 2.5×10^{-3} which corresponds to the reported admixture (8), 97% E2 and 3% M3 and is consistent with that measured by Alburger and Sunyar (9). It can be seen from table 3 that the particle parameter for the 1064 keV transition is in good agreement with theory, although the error is somewhat large. The gamma electron correlation is found to be about 60% attenuated. Nevertheless, the internal conversion coefficient of the 570 keV transition determined from the electron-gamma angular correlation alone is in excellent agreement with the theory. The equation (14) also provides a check for the angular correlation measurements since the ratio formed by the values of the first term (a_o/a_o') of the Legendre Polynomials Series defining the angular correlation function and the areas under the conversion electron peaks in the singles

TABLE 5

Relative Gamma Ray Intensities

Transition Energy (keV)	Relative Gamma Ray Intensity	Relative Intensity of the Transition
570	1	1
1064	0.776 ± 0.063	0.87
1770	0.057 ± 0.004	0.08

spectrum must be unity. A second advantage of deriving the internal conversion coefficients from one angular correlation (electron-gamma or gamma-electron) experiment instead of two is that it allows one extra time which may be utilized to improve upon the statistics of the experimental data. The value of α_K for the 1064 keV transition seems to be slightly lower than the tabulated value. This could be due to any or all of the following reasons:

(1) The ratio, x/y, used in calculations may not be exactly correct;

(2) The electron detection efficiencies for 1064 keV transition may be slightly less than unity as assumed;

(3) The 1064 keV transition which has been assumed to be a pure M4 transition may have an admixture of E5 radiation.

ANOMALOUS K-CONVERSION COEFFICIENT OF 124 keV TRANSITION IN ^{131}Cs

Sen and Dohan (16) reported e-γ and γ-e directional correlation measurements on the 620-124-0 keV cascade in ^{131}Cs. They assigned a spin sequence $\frac{3}{2}^+ \rightarrow \frac{5}{2}^+ \rightarrow \frac{5}{2}^+$ to the cascade and presented experimental evidence for the presence of electric monopole, E0, electron transitions in direct competition with M1 and E2 internal conversion transitions from 124 keV level to the ground level.

Kelly and Horen (15) made an extensive study of ^{131}Cs. From their measured values of $L_I/L_{II}/L_{III}$ ratio, they concluded that the 124 keV transition is predominantly E2 radiation with a possible 8% M1 admixture. They also reported that the 496 keV transition is almost a pure M1 transition. Sen and Dohan (16), however, showed that the 496 keV transition has a (23 ± 7)% E2 admixture.

Following our earlier work, a detailed study of the internal conversion process in the 496 keV - 124 keV cascade transitions was undertaken by us. We used our new approach to determine the K-conversion coefficients for the 496 keV and 124 keV transitions from γ-e angular correlation measurements.

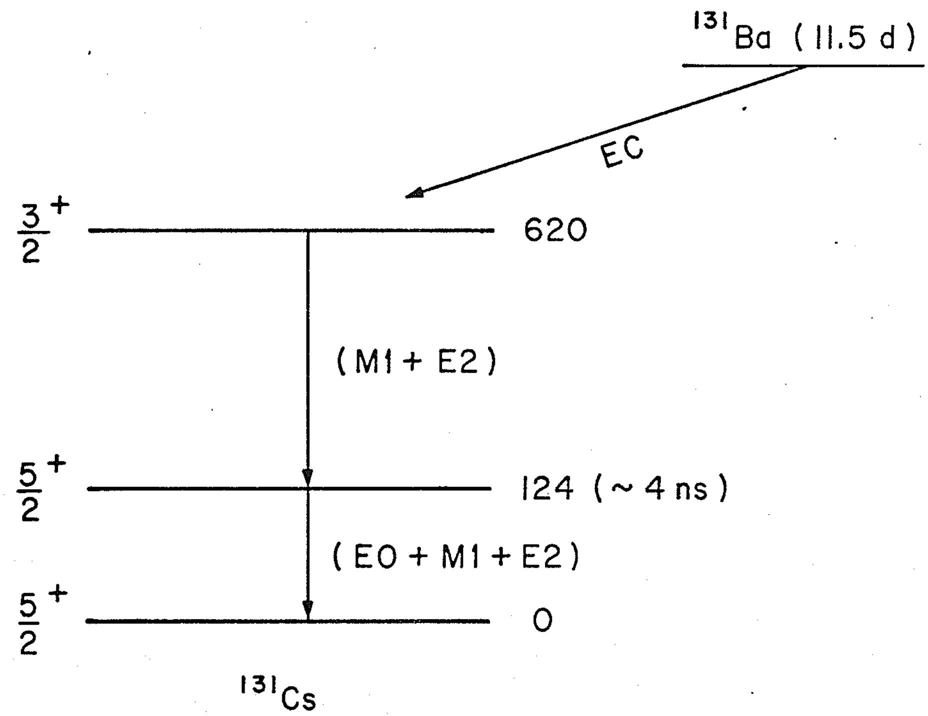
EXPERIMENTAL RESULTS AND THEIR INTERPRETATION

Figure 10 shows the 620-124-0 keV cascade of ^{131}Cs. For the 496 keV transition with a possible (23 ± 7)% admixture the theoretical value of α_K = 0.0101 which may be compared with measured values of 0.0105 ± 0.0100 by Haskins (17), 0.012 ± 0.002 by Kelly and Horen (15) and our experimental value of 0.0100 ± 0.0007. The theoretical value (7) of α_K for the 124 keV transition assuming 100% E2 radiation is 0.610 while on the basis of an 8% M1 admixture (15) it is 0.595. Our present measurement gives the value 0.742 ± 0.077 for α_K which is about 25% higher than the theoretical value assuming an 8% admixture. An earlier measurement gave α_K = 0.39 ± 0.04 (18) for this transition. Kelly and Horen (15) obtained by the Internal External Conversion method the value of α_L = 0.23 ± 0.04. Using their K/L ratio of 3.0 ± 0.2 for this radiation a value of α_K = 0.69 ± 0.14 is obtained. Thus the verification of our direct measurement of α_K is furnished indirectly by Kelly and Horen's α_L and K/L ratio.

Further verification that our value of α_K for the 124 keV transition is correct has been obtained by comparing $\frac{\alpha_{K124}}{\alpha_{K496}}$ with the previous direct measurements (15,18) of this ratio. Also, the relative conversion electron intensities as well as the relative gamma ray intensities obtained indirectly using the measured values of α_K agree well with those directly measured in this laboratory and elsewhere (19).

FIGURE 10

620-124-0 Cascade of ^{131}Cs


^{131}Ba (11.5 d)
EC
$\frac{3}{2}^+$
620
(M1 + E2)
$\frac{5}{2}^+$
124 (~ 4 ns)
(E0 + M1 + E2)
$\frac{5}{2}^+$
0
^{131}Cs

Tables 6 and 7 list the results obtained by us and show their comparison with the theory and previous work. For the theoretical value of α_M we used Rose's tables (20) and for α_K and α_L the tables of Sliv and Band (7). The theoretical value of the K/(L + M) ratio for 124 keV transition has to be corrected for the contribution by E0 electron conversion contribution which is discussed later.

The large value of α_K can be explained, as stated previously, as due to the penetration effects of E0, M1 and E1 transitions. In cases of M1 and E1 transitions the anomaly is possible only if the selection rules are such that the gamma radiation is retarded and the penetration matrix element is not retarded or less retarded as compared, for example, to single particle (Weisskopf) predictions.

The measured (21) half-life of the 124 keV level is $(3.77 \pm 0.05) \times 10^{-9}$ sec. Using our experimental value of $\alpha_{total} = 1.07$ and mixing ratio given by Kelly and Horen (15) we determined the experimental gamma ray transition probabilities of M1 and E2 transitions from the 124 keV level to the ground level. These are shown in table 8.

It is evident from table 8 that the M1 component of the 124 keV transition is strongly retarded while the E2 component is enhanced. An excess of conversion electrons therefore may not necessarily be due to the presence of E0 electrons alone.

TABLE 6

Internal Conversion Coefficients

Quantity	Previous Work[15]	Theory[7]	Present Work Experiment	Present Work Expt./Theory
α_{K124}	0.69 ± 0.14	0.595 (92% E2 + 8% M1)	0.742 ± 0.077	1.25 ± 0.13
α_{K496}	0.012 ± 0.002	0.0101 (77% M1 + 23% E2)	0.0100 ± 0.0007	0.99 ± 0.07
$\frac{\alpha_{K124}}{\alpha_{K496}}$	60 ± 25 65 ± 5[19]	59	74 ± 9	1.26 ± 0.15

TABLE 7

Relative Gamma-Ray and Conversion Electron Intensities

Quantity	Present Work		Previous Work[15]
	Direct Measurements	Indirect Measurement	
$\frac{N_{\gamma 496}}{N_{\gamma 124}}$	1.86 ± 0.09	1.90 + 0.25	1.75
$\frac{N^{e}_{K496}}{N^{e}_{K124}}$	0.026 ± 0.002	-	0.027

TABLE 8

Gamma-ray Transition Probabilities of the 124 keV Transition

Multipolarity	Theory	Experiment	Expt./Theory
E2	1.4×10^{6} Sec^{-1}	8.2×10^{7} Sec^{-1}	58
M1	5.1×10^{10} Sec^{-1}	7.1×10^{6} Sec^{-1}	1.4×10^{-4}

It may also be that the M1 conversion coefficient is abnormally large. It is therefore necessary to examine this possibility. The parameter that plays an important role in the determination of the penetration matrix element for M1 transition is λ defined (21) as the ratio of the new penetration matrix element, M_e, and the corresponding gamma ray matrix element M_γ, in M1 transitions. The value of λ depends on the specific assumptions made about nuclear structure. The admixture of E0 is measured by the quantity

$$q^2 = \frac{\text{E0 K-shell conversion probability}}{\text{E2 K-shell conversion probability}}$$

$$= W(E0)/\alpha_K(E2)W_\gamma(E2) \qquad (17)$$

In the theory of Church, Rose and Weneser(22), the experimental internal conversion coefficient for a given mixing ratio, δ, is given by

$$\alpha_K(E0 + M1 + E2) = \frac{(L + q^2)\ \alpha_K(E2) + \delta^2 \beta_1^K(\lambda)}{(1 + \delta^2)} \qquad (18)$$

Where the K-shell conversion coefficient of the M1 radiation is expressed as

$$\beta_1^K(\lambda) = \alpha_K(M1)\left[1-(\lambda-1)\ C(Z,K)\right]^2 \qquad (19)$$

C(Z,K) is a weighting parameter calculated by Church and Weneser.

It should be possible to determine λ and q from our experimentally determined value of $\alpha_K(E0 + M1 + E2)$ and the gamma-electron angular correlation coefficient $A_{22}(\gamma e)$ which is very sensitive to small admixtures of E0.

The E0-E2 term which makes the angular correlation function sensitive to E0 admixture is given by

$$(qb_o)/(1 + p^2 + q^2) \text{ where}$$

$$p^2 = \delta^2 \sqrt{\beta_1^K(\lambda)/\alpha_K(E2)}$$

and b_o is the interference parameter (22). Although the γ-e angular correlation measurement (16) indicated strongly the presence of E0 transitions the value of $A_{22}(\gamma e)$ was not used for evaluation of λ and q because of its large error. The fact that the admixture of M1 deduced (15) from $L_I/L_{II}/L_{III}$ ratio is not significantly different from that obtained from γ-γ angular correlation measurements (17) indicates the absence of any noticeable anomaly in M1 conversion process i.e. we can assume $\lambda \sim 1$ in equation 18, which then yields a value of 0.26 ± 0.14 for q^2 from equation 18. To check the validity of our assumption, $\lambda \sim 1$, we used the values of q^2 to estimate K/(L + M) ratio by relating it in the following way,

$$\frac{K}{L + M} = \frac{(1 + q^2)\,\alpha_K(E2) + \delta^2\alpha_K(M1)}{q^2\alpha_K(E2)\left[1 + \frac{M(E0)}{L(E0)}\right]\frac{L(E0)}{K(E0)} + \alpha_L(E2) + \delta^2\alpha_L(M1) + \alpha_M(E2) + \delta^2\alpha_M(M1)} \quad ($$

The M(E0)/L(E0) and L(E0)/K(E0) ratios for E0 transitions were obtained from calculations of Church and Weneser (3) and α_K, α_L values from tables of Sliv and Band (7). The values of α_M taken from Rose's tables (20) are not corrected for nuclear size and screening effects.

The K/(L + M) ratio of 2.53 ± 0.29 thus obtained agrees reasonably well with the measured value of 2.28 ± 0.10 lending support to our assumption that the penetration effect of M2 transition is negligible in the present case.

The electric monopole transition probability W(E0) as determined from equation using measured values of q^2 and the half life (21) of the 124 keV level, is 1.3×10^7 sec.$^{-1}$. Finally matrix elements for the E0transition and the E0 strength para-memter ρ (table 9) was determined from the known (3) function.

$$\Omega\ (Z,K) = \frac{W(E0)}{\rho^2} \qquad (21)$$

DISCUSSION

The importance of the study of E0 transitions is that it gives the magnitude of the nuclear strength parameter, ρ, which requires for its interpretation, specific nuclear models. Until now data on E0 transitions were obtained solely from the study of a few cases of $0^+ \to 0^+$ and still fewer cases of $2^+ \to 2^+$ transition all in even nuclei and one case of $\frac{1}{2}^+ \to \frac{1}{2}^+$ transition in an odd mass nucleus. The present work apparently

TABLE 9

Experimental Results on E0 Transitions

Isotope	Energy (keV)	Spin Sequence	q^2	W(E0)	$\lvert\rho\rvert$
^{131}Cs	124	$\frac{5}{2}^+ \rightarrow \frac{5}{2}^+$	0.26 ± 0.14	1.3×10^7 sec^{-1}	0.07 ± 0.02

is the second to consider E0 transition in odd mass nucleus. The theoretical considerations of the present results may bring out some interesting features of the specific nuclear models used in the theory of internal conversion process.

DISCUSSION OF ERRORS

The most important source of error in the work comes from the measurement of areas under the peaks. The statistics for the γ-e experiment were not good and resulted in the largest of the statistical errors (4%) in the various measurements. The K/(L + M) ratios had errors of nearly the same order. The errors in solid angle of the electron detector and the x/y ratio were comparatively small. These gave an overall error of about 6% in the values of K-conversion coefficients.

Because of the poor statistics of the γ-e experiment $A_{22}(\gamma e)$ and $A_{44}(\gamma e)$ have large errors. In the case of $A_{44}(\gamma e)$ for instance, the error is as large as about 150% but because of our new approach it has not affected the value of error in α_K for 570 keV transition.

SUMMARY

The values of K-conversion coefficients obtained by using our new approach are quite accurate and their agreement with theory is good. Our γ-e angular correlation was perturbed by about 60%. Since our new approach is independent of any perturbation in angular correlation measurements, the value of the K-conversion coefficient of 570 keV transition is in excellent agreement with theory and measurements of others (14). This shows the usefulness of our approach in determining K-conversion coefficients in cases where the angular momentum may be perturbed.

The anomalously large K-coefficient of the 124 keV transition in ^{131}Cs is, in our opinion, explainable in terms of the contribution by the E0 electric monopole transition.

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