GAMMA-RAY SPECTROSCOPY OF

PROTON IRRADIATED STRONTIUM

A Thesis Submitted to

the Faculty of Graduate Studies

In Partial fulfillment of the Requirements

for the Degree Master of Science

at

The University of Manitoba

by

Melford Irving Gusdal

December 1968

ABSTRACT

The gamma-ray spectra of ^{85}Y and ^{85m}Y were studied with two Ge(Li) gamma-ray spectrometers. One was a high resolution spectrometer employing a planar Ge(Li) crystal with an active volume of 1.5 cc. The second spectrometer used a large volume coaxial Ge(Li) crystal which had comparatively high photopeak efficiency.

Gamma-gamma coincidence experiments were performed with a large volume coaxial Ge(Li) detector and a NaI(Tl) detector, simultaneously collecting true, random, photo-peak and Compton contributions on a two dimensional multi-channel analyzer.

Forty-two transitions were observed, thirty-seven originating from the decay of 4.7 hr. ^{85}Y and five due to the decay of ^{85m}Y. Six new transitions are reported here, four due to high resolution studies of complex peaks and two due to the use of the large volume, more efficient detector.

The present data are consistent with the decay scheme of Horen and Kelly, indicating levels at 231.1, 237.7, 742.2, 767.7, 801.9, 1150.9, 1261.4, 1353.1, 1625.8, 2123.5, 2171.4, 2324.8, 2351.7 and 2781.1 keV. Evidence is also given confirming the proposed 802 keV level and indicating the possible addition of levels at 978.5, 1404.6 and 2818.7 keV.

Three transitions at 1317.3, 2747 and 3009 keV have not been fitted into the decay scheme.

ACKNOWLEDGEMENTS

The author wishes to express his sincere appreciation to his research supervisor, Dr. K. I. Roulston, for his constant encouragement and advice throughout the entire course of this study.

Sincere thanks must also be extended to Dr. R. A. Brown for his invaluable advice on experimental procedure and to Dr. W. R. Wall for his kind assistance with electronic difficulties.

The author is greatly indebted to Messrs. P. Bonsor and W. Mulholland and the other members of the cyclotron staff for their help in performing the irradiations during this study.

The financial assistance of the National Research Council, Canadian Kodak Corporation and the University of Manitoba Faculty of Graduate Studies is gratefully acknowledged.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

1.1 INTRODUCTION

When a nucleus is bombarded with high energy particles, a nuclear reaction takes place during which the target nucleus is either raised to an excited energy state or is transformed into a different nucleus.

An excited nucleus is unstable and will attempt to lose its additional energy and de-excite to a more stable state which may be either a metastable state or the ground state. This de-excitation is accomplished mainly through electromagnetic transitions, of which there are two basic types:

(a) Emission of a photon or gamma-ray

(b) Transferral of energy to an inner orbital electron ... called internal conversion.

In most cases the target nucleus has been transformed into a new nucleus that will then decay by either

(a) Emission of a particle such as β^+, α, etc. or

(b) electron-capture.

In both methods a daughter nucleus will be formed in either one of its excited states or the ground state. If an excited state is produced, it will tend to de-excite in the manner explained above.

Many different models have been proposed in an attempt to explain the structure and properties of the nucleus. Although some models differ radically as to the exact structure of the nucleus they are all forced to recognize the presence of discrete energy levels in the nucleus and the fact that each nucleus also has its own peculiar set of energy levels along with their associated spins and parities. The most basic models, are

(i) Shell model

(ii) Liquid drop model

(iii) Collective model

(iv) Optical model

with variations of each being used to explain experimental fact.

By making calculations based on one or more of these models, one can predict the level structure of a nucleus, complete with the energy, spin and parity of the various levels.

Through the experimental investigation of the properties of the emitted particles and gamma rays one is able to obtain a similar set of information about the nuclear structure. It is by comparing these two sets of information that one hopes to gain a clearer insight into the structure and mechanism of the nucleus. This is, in effect, the purpose of nuclear spectroscopy; - to construct decay schemes for various nuclei and compare them to theoretical calculations.

With the recent introduction of solid state lithium drifted germanium detectors, [Ge(li)], (Freck 1962) and their subsequent vastly

improved resolution over that of NaI(Tl) detectors, much more refined spectroscopic investigations are possible.

Typical resolutions of Ge(Li) detectors are a factor of ten or more over those of NaI(Tl) detectors. This enables one to resolve gamma rays of closely spaced energy which had up until this time been inseparable on NaI(Tl) detectors. Another by-product of Ge(Li) detectors is more accurate energy measurements. The Ge(Li) detectors themselves, along with the associated electronics, are constantly being improved resulting in detectors with resolutions, to date, of around 1 keV.

The major drawback to Ge(Li) detectors has been their small physical volume and consequently low efficiency, but this is also changing due to improved drifting techniques. With the recent introduction of co-axial drifting techniques, it is becoming possible to produce large volume Ge(Li) detectors with relatively good efficiency and still obtain good resolution, as has been demonstrated by Tavendale et al (Tavendale 1966).

With the continual advancement in technology it appears as though there is much work yet to be done in the field of nuclear spectroscopy.

Yttrium-85 was first reported by Caretto and Wiig (Caretto 1952) who assigned a half-life of 5 ± 1 hr. to it. Dostrovsky et al (Dostrovsky 1963) carried out a study of ^{85}Y and concluded that the 70-min. ^{85m}Sr fraction had a parent with a 2.68 hr. half-life which was subsequently assigned to ^{85m}Y. This conclusion was also reported by Maxia, Kelly and Horen (Maxia 1962, Horen 1962) although Patro and Basu (Patro 1962) did not recognize the existence of two isomers of ^{85}Y.

Horen and Kelly (Horen 1966) recently carried out another study of the gamma-spectrum and proposed a slightly different decay scheme than was previously reported, with a few tentative levels and unplaced gamma rays. Present in this decay scheme were several doublets, which in the gamma spectrum appeared as possibly two or more unresolved gamma energies.

It was due to the above facts, plus the fact that equipment with higher resolution was available that the present study was undertaken.

^{85}Y and ^{85m}Y were produced in the nuclear reaction

$$^{86}Sr(p,2n)^{85}Y\ *$$

^{85}Y and ^{85m}Y decay by β^+ emission and electron capture, leading to excited states in ^{85}Sr and ^{85m}Sr.

CHAPTER II

A. GAMMA RAY SINGLES SPECTRUM

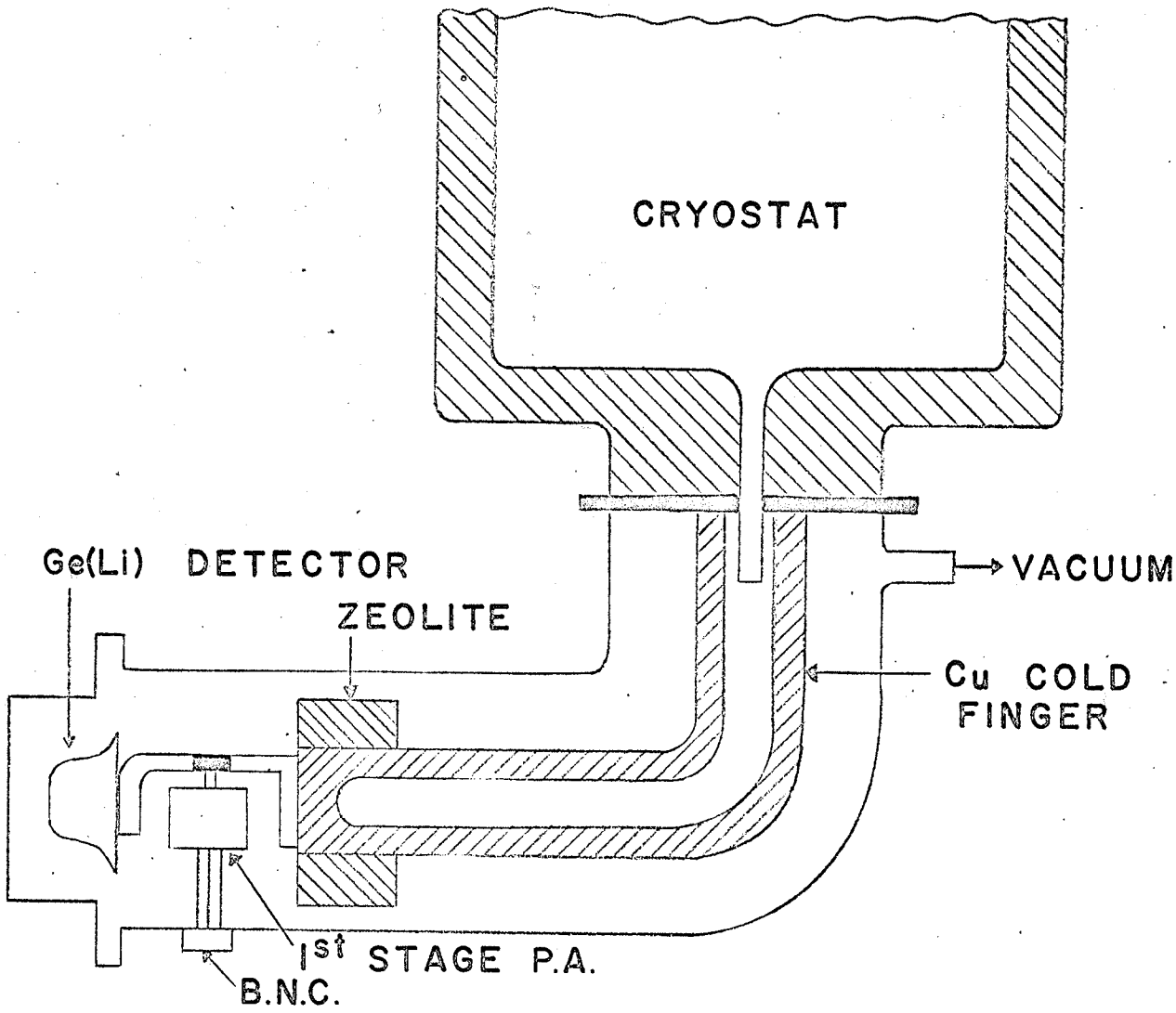
2.1 Instrumentation

The γ-ray spectroscopic studies in this research work were carried out with the utilization of two lithium drifted germanium detectors. One detector was a planar Ge(Li) detector with a depletion depth of 4 mm. and a volume of 1.5 cc. (Model LG 1.5-4). This was coupled to an FET pre-amplifier (TC 130) and a linear amplifier (TC 200). This system was capable of achieving a resolution of 2.5 keV F.W.H.M. at 662 keV.

The other Ge(Li) detector used was co-axial with an active volume of 20 cc. Pulse amplification was achieved by using an FET pre-amplifier (C 403) and a linear amplifier (C 115). This particular system yielded a resolution of 5.6 keV F.W.H.M. at 662 keV.

Both Ge(li) detectors had to be constantly maintained at liquid nitrogen temperatures to minimize leakage currents and to prevent the Li ions from diffusing from their lattice sites in the drifted region. This was accomplished by the use of a 10 l. "chicken-feeder" resevoir on the high resolution detector and a 20 l. "chicken feeder" resevoir on the large volume detector.

Figure 2-1 shows the internal view of a typical Ge(Li) detector and cryostat assembly.



CRYOSTAT AND DETECTOR ASSEMBLY

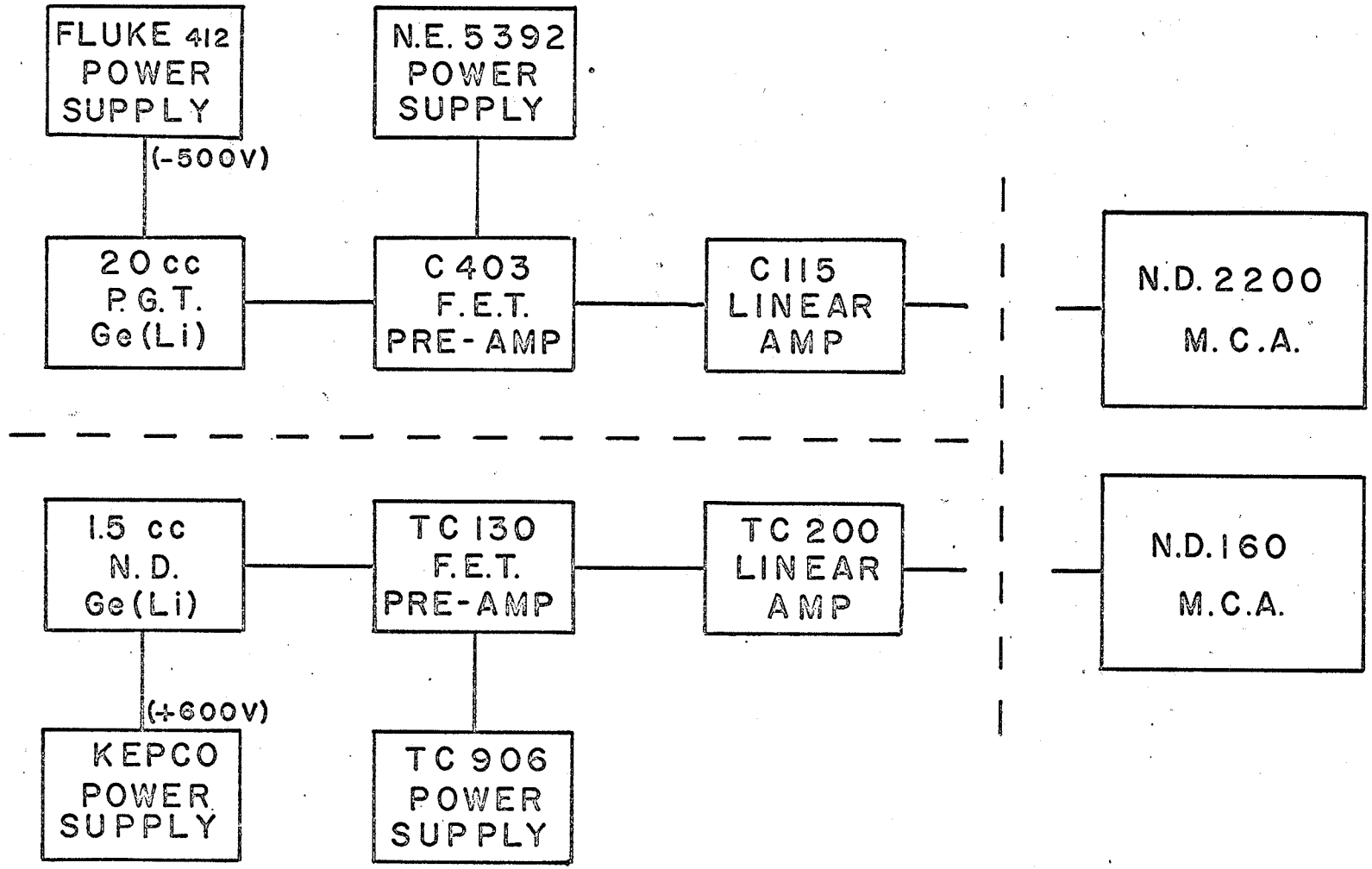
FIGURE 2-1

The smaller volume detector, because of its energy resolution was used for detailed examinations of photo peaks where the presence of doublets was suspected. The large volume detector was used where detection efficiency was an important factor.

A block diagram of the two Ge(Li) gamma ray spectrometers is given in Figure 2-3.

To collect and store the data obtained from the above mentioned detectors, two multi-channel analyzers were available. One was a two-parameter analyzer (Model ND 160 F) with a 1024 channel ADC and a 4096 channel memory. This analyzer could be used in either a one-parameter mode with 1024 channels available, or in a two-parameter mode which facilitated 4 x 1024, 8 x 512, 16 x 256, 32 x 128 and 64 x 64 groupings. Coincidence gating was also available and was used in the coincidence experiments.

The second multi-channel analyzer (MCA) was a Model ND 2200 with three-4096 channel ADC's and a 4096 channel-memory. This unit had the capacity to handle up to four ADC's on a simultaneous time sharing basis with a maximum availability of 4096 channels which however, could be extended with the addition of a larger memory. The ADC's of the ND 2200 had a digitizing rate of 16 MHz while that of the ND 160 F ADC's was only 4 MHz. This gives the above unit much greater flexibility in experimenting as it is capable of handling a much higher counting rate.



Ge(Li) GAMMA SPECTROMETERS

FIGURE 2-3

To obtain a quick analysis of results, an X-Y plotter (Model 20-2) was available. Information could be plotted directly from the MCA memory to yield 10 inch by 16 inch graphs. For larger and more precise graphs, an IBM 1620 computer and associated Calcomp plotter were available. This system was capable of plotting graphs 3 feet wide and had an infinite X-axis. Programmes were devised that gave either a linear plot with scale changes at predetermined positions, or a semi-log plot.

2.2 Experimental Procedure

All the irradiations in this study were performed internally on the 50 MeV sector-focussed cyclotron at the University of Manitoba. Beam currents of up to 2.7 μA at 35 MeV were possible.

The target sources for all the irradiations in this study were in powder form, thus they had to be encapsulated for the purpose of internal irradiations, and also for safety reasons. As a result, the powder was enclosed in a capsule of high purity aluminum foil about 10 μ thick.

Preliminary experiments were performed with naturally occurring strontium as $Sr(NO_3)_2$ and adequate bombarding conditions determined. For the $^{86}Sr(p,n)^{85}Y$, these were a proton energy of 35 MeV at approximately 1 μ A with an exposure time varying from 5 minutes to 30 minutes depending on the strength required.

An enriched sample of ^{86}Sr (84.1%) was obtained and used for subsequent experiments. The impurities were 9.3% ^{87}Sr, 6.6% ^{88}Sr and less than 0.5% miscellaneous impurities. The initial enriched source was non-radio-active, but during irradiations the long lived products of ^{86}Y, ^{87}Y and ^{88}Y were formed making the source radio-active.

A series of irradiations were carried out to determine the cross-sections for reactions with ^{86}Sr. The following qualitative cross-sections were determined:

$^{86}Sr(p,n)^{86}Y$ was favoured at 25 MeV

$^{86}Sr(p,2n)^{85}Y$ was favoured at 35 MeV

$^{86}Sr(p,3n)^{84}Y$ was favoured at 45 MeV.

With the above results plus separate investigations into previous experimental work on strontium, it was decided to concentrate on the $^{86}Sr(p,2n)^{85}Y$ reaction and the subsequent decay of ^{85}Y by β^+ emission and electron capture into levels of ^{85}Sr.

Thus, the balance of the experimenting was carried out using an irradiation energy of 35 MeV at 1μA, varying the exposure period from 5 minutes to 30 minutes depending on required strength.

An investigation into the contribution of the aluminum foil to the gamma spectrum was also carried out. The foil was irradiated at 35 MeV for 1 hour, after which the gamma spectrum was acquired on the large coaxial detector.

If the aluminum foil was left to decay for about 20 minutes most of the spurious activity had died away leaving only two fast decaying peaks at 837 and 1010 keV along with 511 keV annihilation peak and the associated 15 hr. activity of ^{24}Na. Figure 2-4 illustrates the resulting aluminum spectrum acquired 20 minutes after irradiation.

The major object of this study was to further investigate the energy level structure of ^{85}Sr by searching for weak transitions and attempt to resolve various doublets present in the spectrum. For the investigation of weak and high energy transitions, the large volume detector was employed, whereas for the separation of doublets and closely spaced γ-rays, the higher resolution detector was used. However, the efficiency of this latter detector above about 1200 keV is very poor, and consequently due to the short half-life of ^{85}Y (4.7 hr.) and ^{85m}Y (2.9 hr.) this detector yielded very little information above 1200 keV since one had a limited accumulation time.

To enable one to distinguish between the transitions due to ^{85}Y, ^{85m}Y and those of the remaining isotopes of Strontium and other impurities it was necessary to take timed runs for the γ-spectrum. In order to obtain good statistics and yet be able to follow the decay of the 2.9 and 4.7 hour peaks, the analyzer was allowed to accumulate for periods of 20,000 seconds live time. Thus, by integrating the area of the peaks in the resulting γ-spectrum over the above time interval for two or more successive timed runs, the half-life of the decaying nucleus in which they originated could easily be determined.

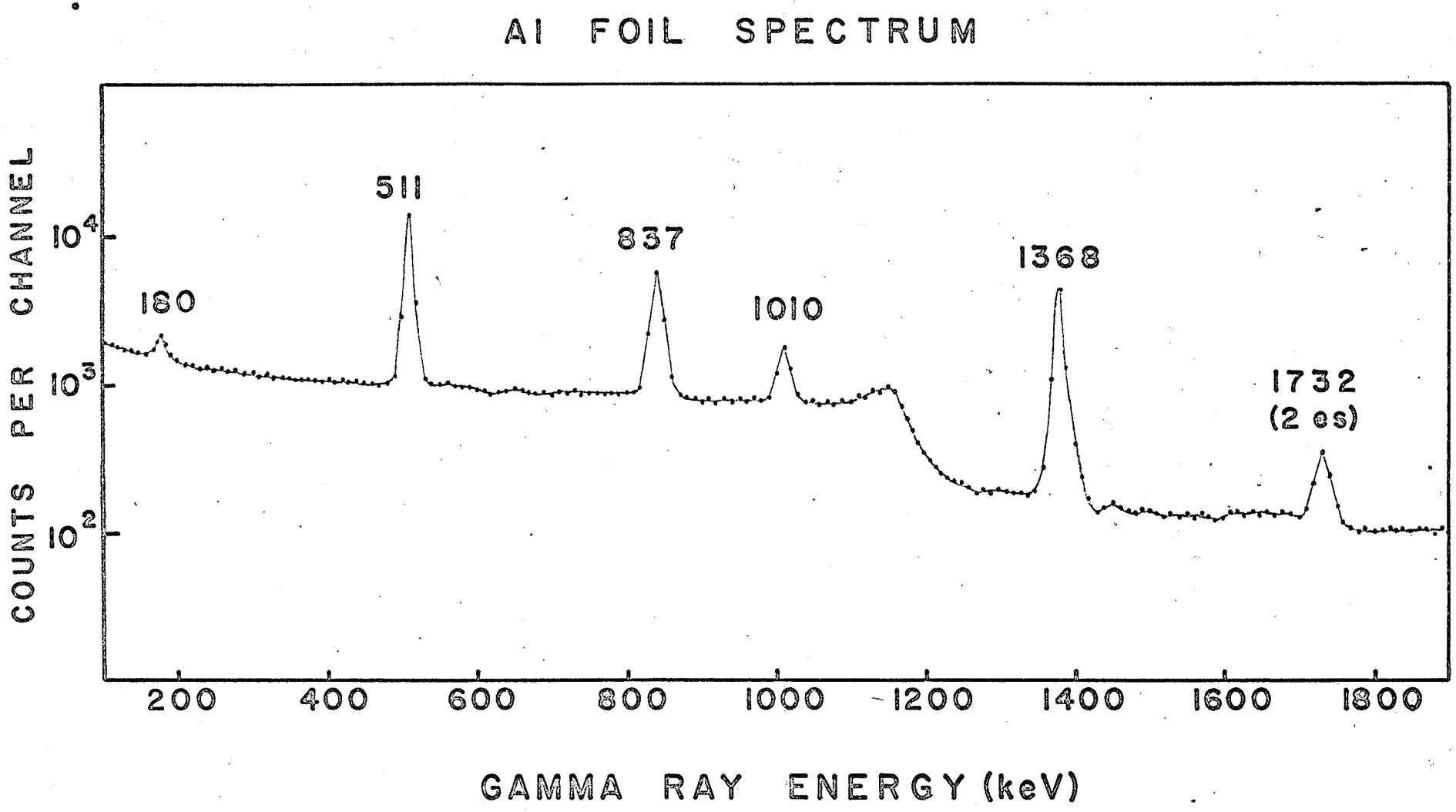

Al FOIL SPECTRUM
COUNTS PER CHANNEL
10^4
10^3
10^2
180
511
837
1010
1368
1732
(2 es)
200
400
600
800
1000
1200
1400
1600
1800
GAMMA RAY ENERGY (keV)

FIGURE 2-4

After the irradiated source had been removed from the cyclotron, it was allowed to decay for about twenty minutes to minimize the contribution to the γ-spectrum of the short-lived γ-rays in the aluminum foil and other short lived impurity contributions. The source was then placed in a predetermined geometry for which the detector had been previously calibrated for efficiency.

Several runs were performed in which sources that contained very accurately measured γ-rays were used both before and after the experiment in order to calibrate the detector. However, for the purpose of very precise energy measurements, simultaneous energy calibrations were employed for two runs. In using this method, the γ-standards were placed just close enough to the detector so that they were plainly discernable in the resulting spectrum. The disadvantage of such a procedure however is that some γ-transitions in the original spectrum are masked over by some of the γ-rays in the calibration standards. Hence both types of singles spectra were very valuable. The source used had a unique property of several well known γ-standards present. These were the 511 keV annihilation line, ^{88}Y lines and ^{24}Na transitions (from aluminum foil), which were used as internal standards for energy calibration.

A list of gamma ray standards used is given in Table 2-1 and was obtained from Hollander's (Hollander 1967) Table of Isotopes.

After each set of runs, the data were first plotted out either manually on linear graph or by the IBM 1620 computer and associated Calcomp plotter. These results were then analyzed to determine energy, intensity and half-life of the photo peaks obtained.

TABLE 2-1 (a)

GAMMA ENERGY CALIBRATION STANDARDS

Calibration Source	Energy (keV)	Reference
^{203}Hg	72.873	(i)
^{109}Cd	87.7	(i)
^{57}Co	121.97	(i)
^{57}Co	136.33	(i)
^{141}Ce	145.43	(i)
^{139}Ce	165.84	(i)
^{192}Ir	205.782	(i)
^{203}Hg	279.17	(i)
^{192}Ir	295.938	(i)
^{192}Ir	308.429	(i)
^{192}Ir	316.486	(i)
^{192}Ir	468.053	(i)
MoC^2	511.006	(i)
^{192}Ir	588.557	(i)
^{192}Ir	604.385	(i)
^{192}Ir	612.435	(i)
^{137}Cs	661.595	(i)
^{58}Co	810.46	(i)
^{54}Mn	834.85	(i)

(i) Hollander (1967)

TABLE 2-1 (b)

GAMMA ENERGY CALIBRATION STANDARDS

Calibration Source	Energy (keV)	Reference
^{56}Co	846.76	(ii)
^{88}Y	897.96	(i)
^{56}Co	1037.99	(ii)
^{60}Co	1173.226	(i)
^{56}Co	1238.38	(ii)
^{22}Na	1274.53	(i)
^{60}Co	1332.483	(i)
^{24}Na	1368.526	(i)
^{56}Co	1360.42	(ii)
^{56}Co	1771.74	(ii)
^{56}Co	2015.45	(ii)
^{56}Co	2034.98	(ii)
^{56}Co	2598.88	(ii)
^{24}Na	2753.92	(i)
^{56}Co	3202.42	(ii)

(i) Hollander (1967)

(ii) Barker (1967)

2.3 Energy Determination

To enable one to fit a decay scheme accurately it is necessary to have as precise energy measurements as possible. The precision of these measurements depends upon many details such as accurate standard calibration sources, non-linearity of γ-spectrometer system, accuracy of peak centre determination plus many other contributions such as system stability.

The first major requirement is to use as many standard calibration sources as possible covering the complete energy range under study. Using these sources, one can calculate the non-linearity of the system by first obtaining the position of the associated γ-rays, and then taking one point close to each end of the spectrum to which a straight line is fitted. A plot of the deviation of the other points from this straight line yields the non-linearity of the system. Figure 2-5 shows the non-linearity of the large volume γ-spectrometer for one of the experimental runs. The gamma ray standards used are listed in Table 2-1 and were obtained from Hollander's Table of Isotopes (Hollander 1967).

In order to obtain the exact position of the γ-ray peaks, one must have an accurate and consistent method of determining the peak centre. The two methods most commonly used are either by finding the centre of a line drawn at half-maximum height or by an extension of this called the 'Top Peak Centre' method. The latter method was the one used in this study and involved plotting the peak on an expanded scale after which several horizontal lines were drawn at various positions in the peak. These lines

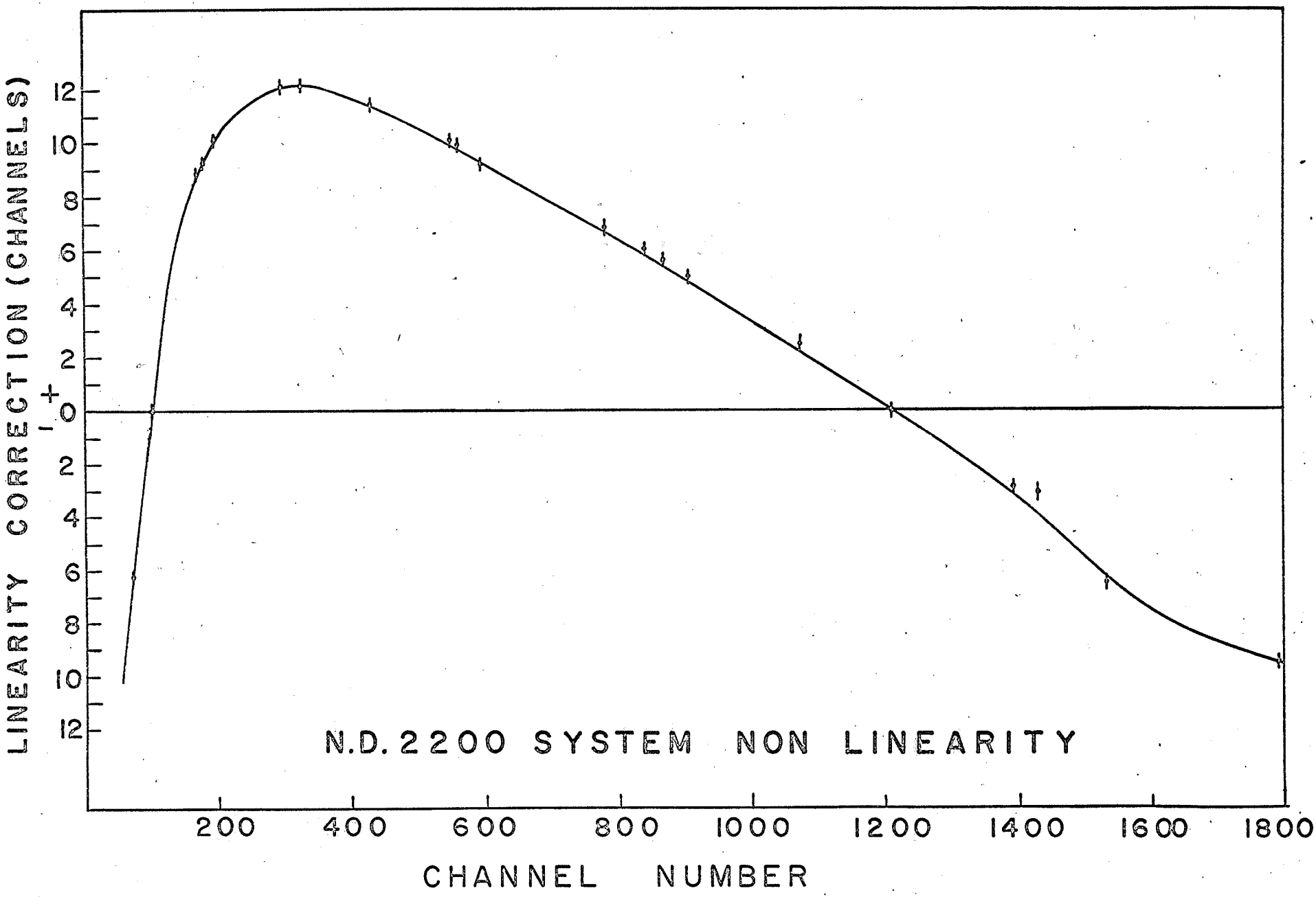

LINEARITY CORRECTION (CHANNELS)
12
10
8
6
4
2
+
0
-
2
4
6
8
10
12
N.D. 2200 SYSTEM NON LINEARITY
200
400
600
800
1000
1200
1400
1600
1800
CHANNEL NUMBER

FIGURE 2-5

were bisected and the centres joined via a straight line that was extended to the top of the peak, the point of intersection being labelled as the peak centre. This method is quite valuable, especially when dealing with asymmetric peaks. With good statistics and careful plotting the peak centre can thus be located to within about 0.1 channels. The particular method chosen is not extremely crucial as long as one is consistent and uses the same method for all calculations.

To obtain the greatest accuracy, it is extremely important to perform simultaneous energy calibrations, as described earlier. This reduces the errors in energy determination due to system stability and non-linearity determination. It is a well known fact that amplifier, analyzers and power supplies drift slightly during operation, which may cause the calibration of the system to shift from the calibration time to the accumulation time.

The non-linearity of a system is affected by the counting rate. This effect can, in principle, be reduced by improving the pulse handling techniques of the pre-ampliers and amplifiers. By using the standard calibration sources for computing the non-linearity, and incorporating them as simultaneous calibration points, the non-linearity of the system while accumulating the desired spectrum is quite accurately obtained.

The detrimental facet of simultaneous calibration is that some of γ-transitions are masked by calibration peaks. This aspect can, in general, be overcome by finding the energy of the other γ-rays and using them as internal calibration points in subsequent runs.

A computer program was also devised which attempted to fit the calibration points to a quadratic equation, but it was found that the energy calibration for the system used obeyed neither a quadratic nor a cubic and the previous non-linearity method proved to be more accurate.

The accuracy of the energy measurements in this study is claimed to be about ±0.5 keV.

2.4 Intensity Measurements

A very instrumental part in determining a decay scheme is the measurement of the relative intensities of the γ-ray transitions. Solid state radiation detectors do not collect different energy γ-rays with equal efficiency due to the variation of absorption and stopping power inside the crystal. For a complete discussion of the various contributing factors to radiation detection the reader is referred to virtually any text on nuclear physics such as Evans (Evans 1955). Hence, due to the dependence of efficiency on energy, the radiation detectors have to be calibrated for efficiency in order to give full meaning to intensity measurements.

The efficiency of the Ge(Li) detectors used in this study was calculated by utilizing a set of energy standards obtained from the International Atomic Energy Agency in Vienna, Austria. The intensities of these sources were very accurately known to within 1% or 2%, thus the absolute efficiency of the detectors was precisely determined. These sources however had an energy range of up to 1332 keV, so to obtain the efficiency at higher energies a ^{56}Co source was also employed. The relative efficiency of this source has been very accurately determined (Barker 1967)

and since its energy range overlapped the preceding set of standards, the relative efficiency curve could be normalized to the previous curve and hence be converted to absolute efficiency. By this method the absolute efficiency for each of the Ge(Li) detectors was determined for two geometries. The efficiency of the detector is reduced as the distance from source to detector is increased; however the general shape of the curve is altered very little, implying that the relative efficiency remains approximately constant for relatively small changes in distance.

According to theoretical calculations (Wanio 1965), the efficiency for small volume detectors should have approximately an $E_\gamma^{-2.5}$ dependence in the range between 100 and 500 keV and an $E_\gamma^{-1.5}$ dependance between 500 keV and 3 MeV. The efficiency curves for the two detectors used in this study were multiplied by an E_γ^2 factor which slightly increases the accuracy of reading the graph over that of a log-log plot. These curves are illustrated in Figure 2-6 and Figure 2-7.

In determining the areas of the photo peaks for intensity purposes, one must first be able to define the background level, which in some cases can be quite difficult. In general, the background counts are due to compton contributions of higher energy γ-rays. However, in most peaks, the region between the compton edge and the photo peak tends to become filled in due to partial re-absorption of compton scattered gamma rays. This effect produces a background on the low energy side of the peak that is at times considerably higher than that on the high energy side.

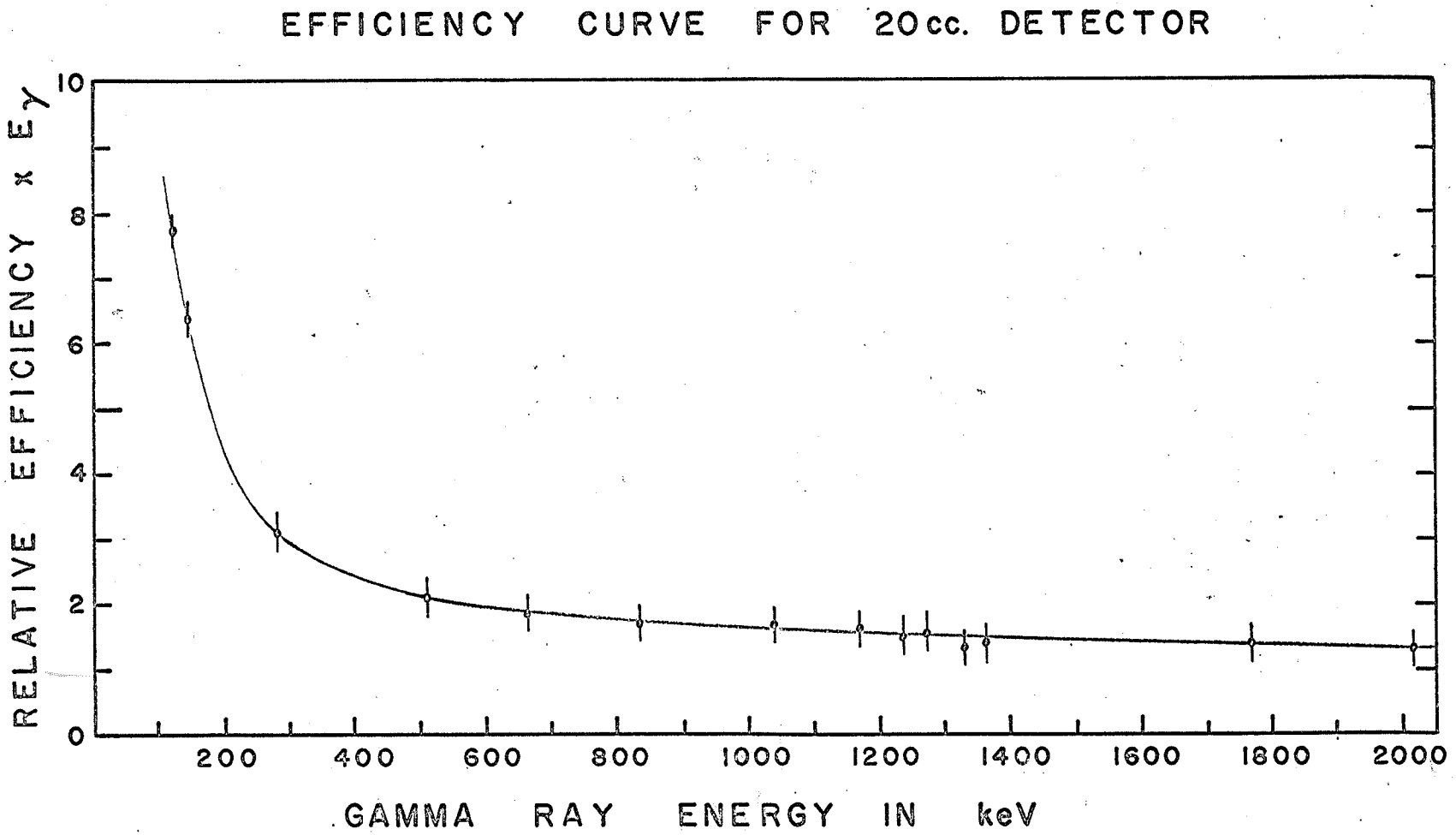

EFFICIENCY CURVE FOR 20cc. DETECTOR
RELATIVE EFFICIENCY x Eγ
0
2
4
6
8
10
200
400
600
800
1000
1200
1400
1600
1800
2000
GAMMA RAY ENERGY IN keV

FIGURE 2-6

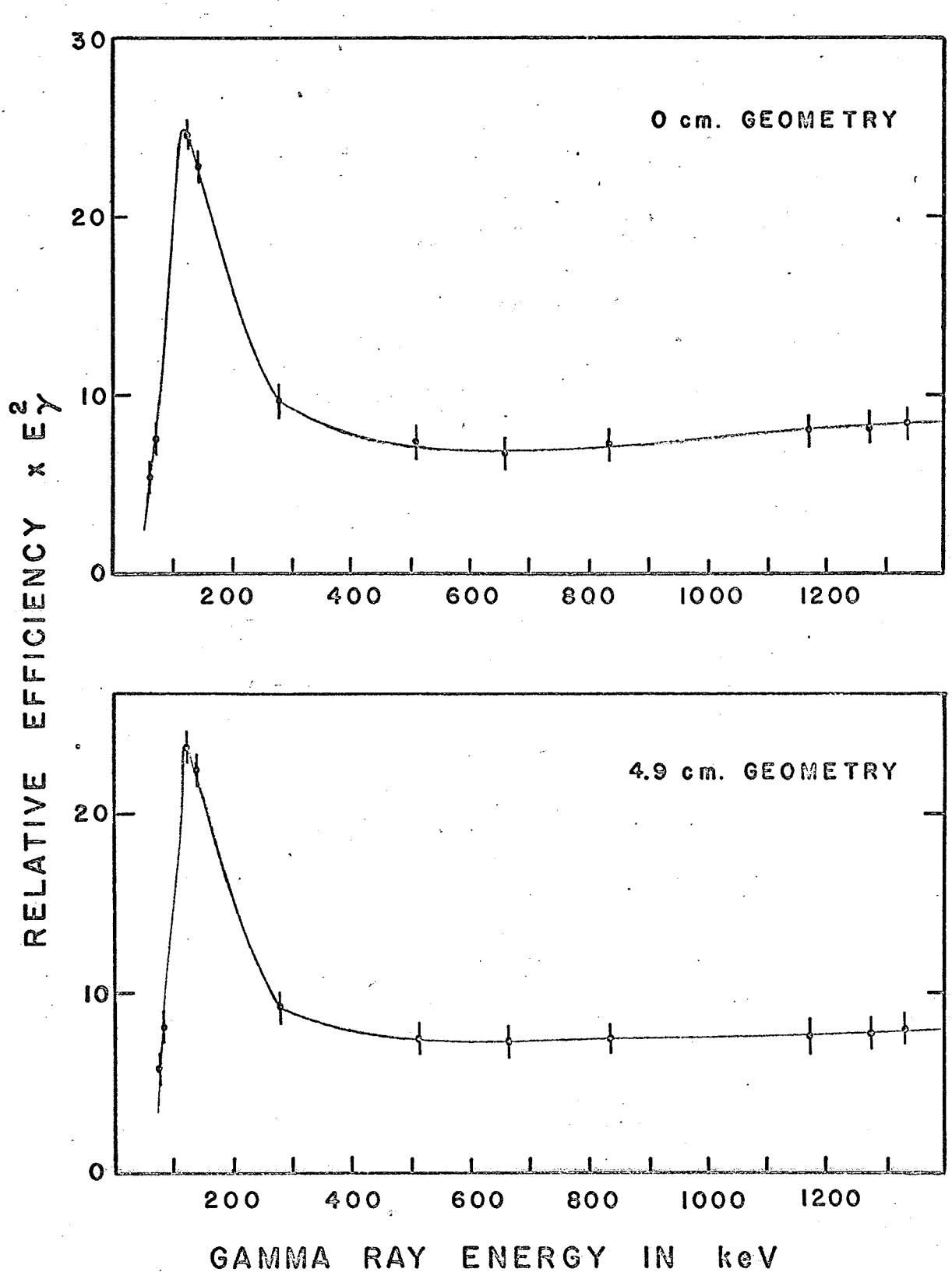

RELATIVE EFFICIENCY LG 1.5-4 DETECTOR
0 cm. GEOMETRY
4.9 cm. GEOMETRY
RELATIVE EFFICIENCY x E_γ^2
GAMMA RAY ENERGY IN keV
0
10
20
30
200
400
600
800
1000
1200

FIGURE 2-7

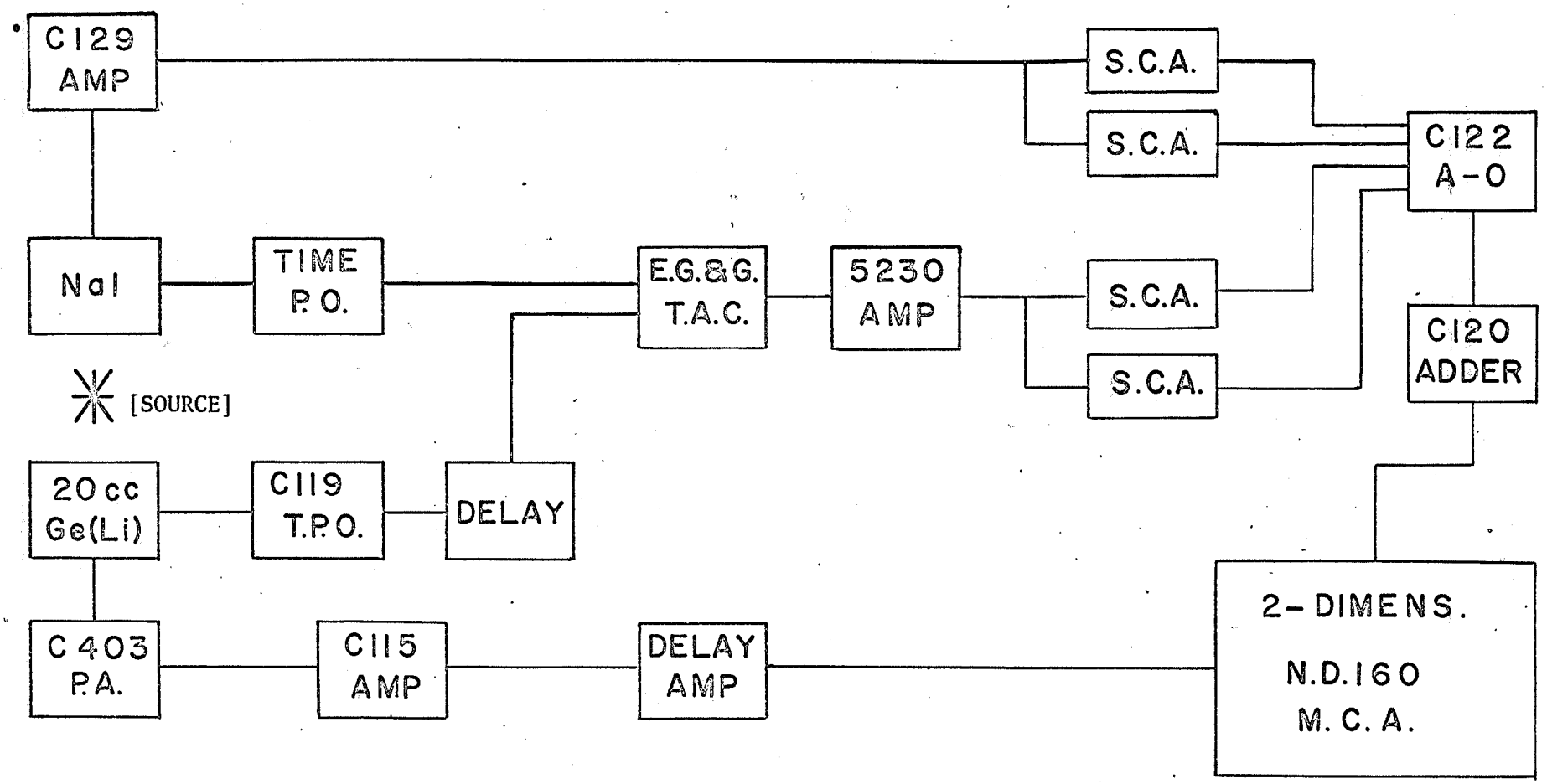
Using the method preferred by Haverfield (Haverfield 1966) who made a detailed study of this problem, the background was determined by joining the point of maximum radius of curvature on the low energy side to the base on the high energy side. The background was then subtracted from the photo peak, after which only those points whose magnitude was greater than 1% of the peak height were retained for area measurements.

B. GAMMA-GAMMA COINCIDENCE

2.5 Instrumentation

To assist in the placement of gamma transitions on the energy level scheme, a gamma-gamma coincidence system was constructed, of which a block diagram is given in Figure 2-8. The system employed a NaI(Tl) detector and a Ge(Li) detector in conjunction with a time to amplitude converter (T.A.C.) and a two parameter multi-channel analyzer.

When a window of a single channel analyzer (SCA) is set on a photopeak, it will also pass contributions due to the compton events of higher energy gamma rays. Similarly, when a window of an SCA is set on the TAC distribution peak it also passes background counts due to random events. Thus, by including four SCA's in the coincidence system it is possible to set windows on a photopeak, the compton background above the photopeak, the TAC distribution peak and the random background above this peak (Figure 2-9) enabling one to simultaneously measure all the contributions to the coincidence spectrum. This is particularly useful when working with



COINCIDENCE SYSTEM

FIGURE 2-8

short lived sources, since it is not necessary to make corrections for the decay of the parent nucleus which would definitely be required if the contributions were accumulated independently.

The NaI(Tl) detector consisted of a 2 inch x 2 inch cylindrical crystal mounted on a photomultiplier which gave out both a linear signal and a fast logic signal for timing purposes.

The large volume Ge(Li) detector was used because of its superior efficiency over the N.D.-LG. 1.5-4. The principle reason that Ge(Li) detectors have not been used in coincidence systems is their relatively poor efficiency as compared to NaI(Tl) detectors. However, with the advent of more efficient, large volume Ge(Li) detectors, it is now becoming very advantageous to employ them due to their high resolution properties.

The ultimate experimental set-up for coincidence work is a system employing two large volume Ge(Li) detectors which offer favourable efficiency as compared to NaI(Tl) crystals to yield a reasonable counting rate. This system would then offer the resolution required to enable one to distinguish coincidence work between γ-rays of closely spaced energy. Such a system is currently in use by G. T. Ewan and associates at Chalk River (Brown 1968) who are doing coincidence work with two 40 cc. Ge(Li) detectors.

2.6 Experimental Procedure

In setting up the coincidence system, the intrinsic difficulty

was due to timing problems. Great care had to be exercised so that the fast time pick-off pulses for both the Ge(li) and NaI(Tl) detectors were in coincidence at the TAC. A delay of about 4 μ seconds was also inserted between the Ge(Li) detector and the MCA in order that the energy pulse arrived at the MCA after the logic gating pulse which was derived from the single channel analyzers (SCA's) via the adder amplifier as shown in Figure 2-8.

The windows on the SCA's were set with the use of a linear gate. A very important facet of this operation was that the output amplifiers of the NaI(Tl) detector and TAC be loaded equivalently during actual performance and while being subjected to the linear gate. An easy way of accomplishing this is by constantly driving another amplifier which in turn operated the linear gate during the setting of the windows.

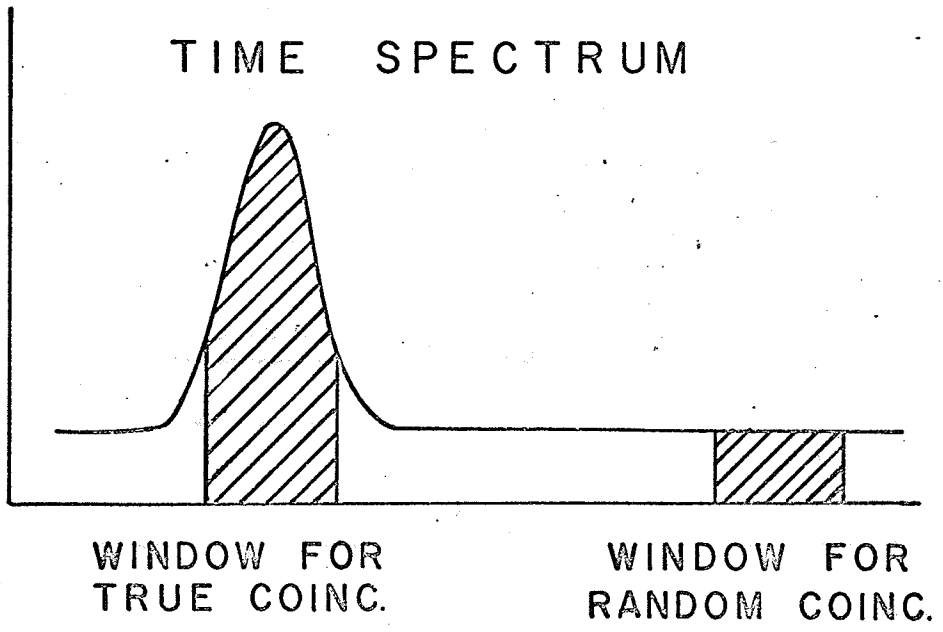
The four single channel analyzers (SCA's) were used to set windows on the energy spectrum and TAC distribution to give the required contributions to coincidence spectrum. Windows were set on the desired γ-ray with which one wanted to do coincidence work, the compton shoulder above this γ-ray, the main peak of the TAC distribution for true coincidences and an equal width window setting above this peak to yield random contributions to the coincidence data. The windows for the energy were set on the NaI(Tl) detector, with the coincidence spectrum being collected with the Ge(Li) detector.

The ND 160 F multi-channel analyzer was used in its two parameter mode to collect the various required contributions to the coincidence spectrum.

The MCA during this set of experiments was used in the 8 x 512 grouping which allowed for accumulation of a singles spectrum plus peak true, peak random, compton true and compton random. The last four contributions were governed by the coincidence requirements of the four SCA's. Figure 2-9 illustrates where each of the four windows were set, two on the time distribution and two on the energy spectrum. The peak true spectrum was derived from coincidence pulses between the TAC distribution peak and the desired photo electric peak and so forth for the other three spectra.

Under subjection to extremely heavy counting rates, the TAC distribution deteriorated rapidly, giving a true to random ratio of about 2:1, or less, hence in preparing the source for the coincidence experiment a compromise had to be made between a weak source which gave a good TAC distribution and a strong source necessary for good statistics. After several coincidence runs were made at various strengths, it was decided to irradiate the source for 10 minutes at 35 MeV and approximately 600 nano Amps. This gave a source with a strength of about 25 - 50 μ C.

For the actual coincidence experiments, the source was prepared in the above manner and the detectors which were in 180° geometry were placed as close to the source as possible and yet yield a good TAC distribution. Due to the low counting rate of the four coincidence contributions, it was arranged to have two irradiations separated by about three half-lives so that meaningful statistics could be obtained. As mentioned previously a single spectrum from the Ge(Li) detector was also accumulated to aid in the identification of the coincidence peaks. This spectrum however had to be anti-coincidenced from the system after a few


TIME SPECTRUM
WINDOW FOR TRUE COINC.
WINDOW FOR RANDOM COINC.

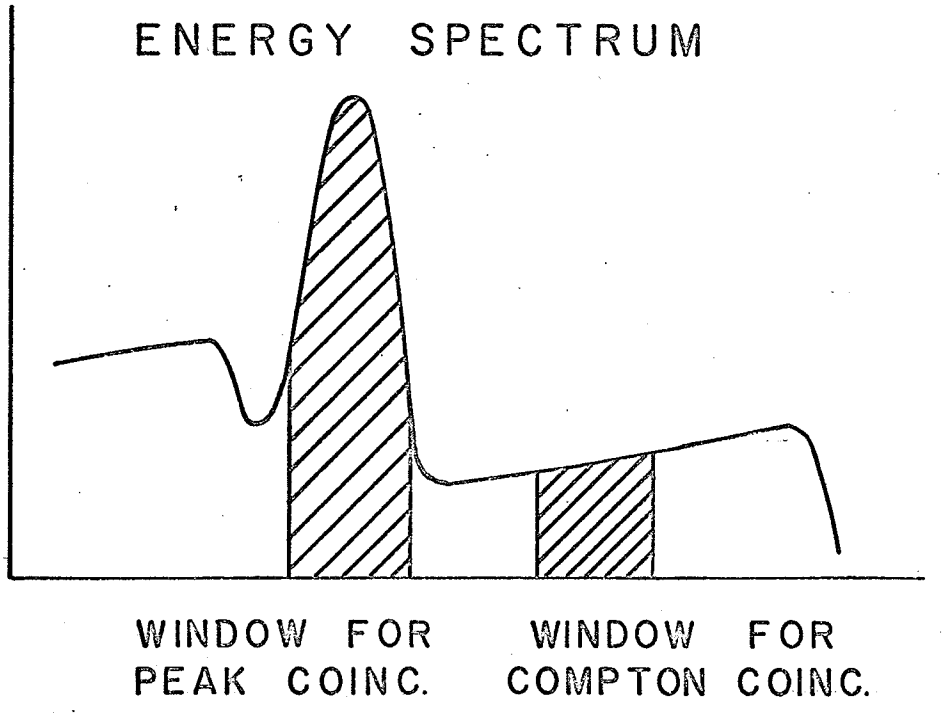

ENERGY SPECTRUM
WINDOW FOR PEAK COINC.
WINDOW FOR COMPTON COINC.

FIGURE 2-9

minutes accumulation time because the singles counting rate was very high and thus resulted in an undesirably large dead time in the MCA.

During this study, a coincidence experiment with the energy gate set on the 231 keV peak was performed. Other coincidence runs would have been of limited use only, due to the closely spaced energy levels present and the poor resolution of the NaI(Tl) detector used for the energy selection.

The analysis of coincidence data was accomplished by utilizing the four previously described coincidence spectra in the following manner.

The window set on the photo peak collects events due to both the photo peak and compton events of higher energy gamma rays. Similarly the window set on the TAC distribution peak for true events also contains a background due to random events. Therefore, the net events for the photo peak are

(peak true - peak random) .. .. (1)

or abbreviated (P.T. - P.R.)

The net events due to compton background are

(Compton true - compton random) .. .. (2)

or abbreviated (C.T. - C.R.)

Thus, actual number of real coincidence events are given by

$$N = (P.T. - P.R.) - (C.T. - C.R.) \quad .. \quad .. \quad .. \quad .. \quad .. \quad (3)$$

The singles spectrum that was simultaneously collected with the coincidence data was used to help in the identification of the peaks in the coincidence spectrum. Figure 3-4 shows the Eγ-231 spectrum obtained in this experiment.

CHAPTER III

THE DECAY OF ^{85}Y AND ^{85m}Y

3.1 Discussion of gamma singles spectrum

In the analysis of the gamma spectrum, the major concern was the differentiation of the 4.7 hr. and 2.9 hr. activity due to ^{85}Y and ^{85m}Y respectively, from that due to other yttrium isotopes that were formed during the irradiation. Also present were lines due to the aluminum encasement for the strontium powder (Figure 2-4) and also lines from ^{85}Rb, especially the 150 keV transition, as shown in Figure 3-1(a).

The 231 keV peak is quite intense, containing contributions from both 2.9 hr. and 4.7 hr. activity. Totally unnoticed at a first glance are two peaks on the high energy tail (insert on Figure 3-1(a)) both of which appear to have a 2.9 hr. half-life. Their energies are 235.5 keV and 237.6 keV, the latter of which is the transition to ground of the 70 min. metastable state. The 235.5 keV peak has not been reported before and its position in the decay scheme can only be postulated as there is no coincidence data for 2.9 hr. activity due to the 70 min. metastable 237.6 level.

In Figure 3-1(b), the high resolution of the small detector becomes very important. The 504.5 keV transition which Horen and Kelly were unable to separate from the 511 keV annihilation peak in their gamma

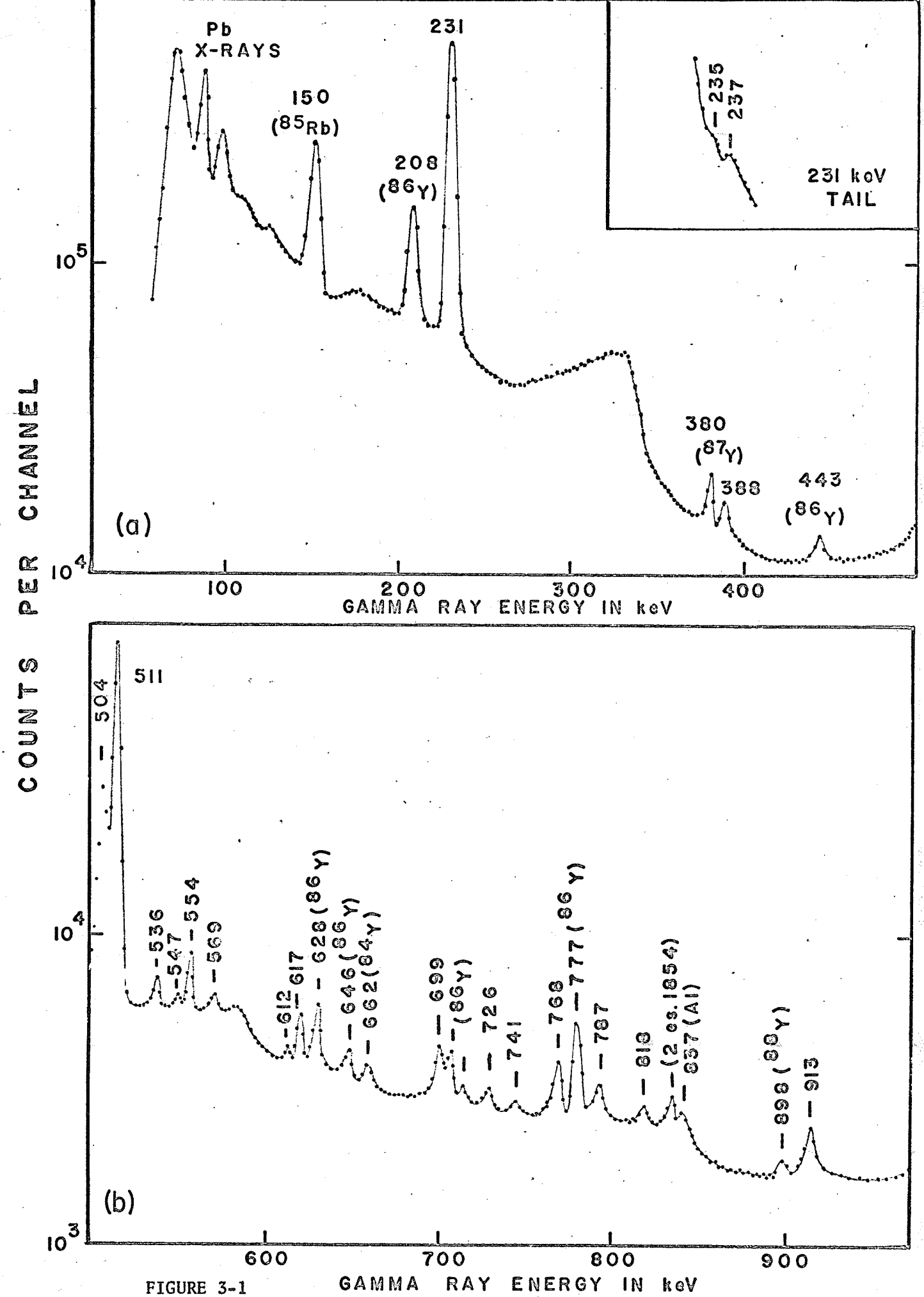

Pb
X-RAYS
231
150
(85Rb)
208
(86Y)
231 keV
TAIL
235
237
380
(87Y)
388
443
(86Y)
(a)
COUNTS PER CHANNEL
10^5
10^4
100
200
300
400
GAMMA RAY ENERGY IN keV
511
504
536
547
554
569
612
617
628(86Y)
646(86Y)
662(84Y)
699
(89Y)
726
741
768
777(86Y)
787
818
(2 esc.1854)
857(Al)
898(89Y)
913
(b)
10^4
10^3
600
700
800
900
GAMMA RAY ENERGY IN keV

FIGURE 3-1

singles spectrum is here clearly visible. Also, the previously reported 540 keV and 550 keV transitions were resolved into the four gamma rays with energies of 536, 539, 547 and 554 keV. The 539 keV transition must be considered as only tentative since the resolution is not good enough to completely separate it from the 536 keV peak and it could not be accomodated in the present decay scheme. The 547 transition on the other hand is quite well separated and definitely has 5 hr. activity. The only place in the decay scheme which would allow for this energy is a transition between the 2171 and 1625 keV levels and it has tentatively been placed there.

The 614 keV doublet observed by Horen and Kelly was resolved on the small high resolution detector into photo peaks with energies of 612.5 keV and 617.5 keV. However, the 617.5 keV photo peak was clouded by an unknown 620 keV gamma ray with a 15 hr. half-life, probably from ^{86}Y.

A 741 keV transition with a 2.9 hr. half-life was observed. This transition was not observed by either Dostrovsky (Dostrovsky 1963) or Horen and Kelly (Horen 1966) although Patro and Basu had previously reported a transition in this energy range (Patro 1962). The gamma-ray is weak and could possibly be a transition to ground, which one would expect to be small due to the large spin change of $(\frac{1}{2}, \frac{3}{2}^-) \rightarrow \frac{9}{2}^+$ involved (Figure 3-7).

During an extended period of accumulation, on the large volume Ge(Li) detector a weak transition at 801.9 keV was found that had been previously unobserved.

The energy of the 861 keV peak has larger uncertainty than most other peaks due to its position on the edge of a compton shoulder. This makes it very difficult to find the peak centre and the peak area due to the uncertainty in the background level, as was discussed in Chapter II.

The third portion of the spectrum is shown in Figure 3-2(a). It contains ten gamma rays from ^{85}Y decay, one of which is a double escape peak. The complex of three peaks at 1395, 1405 and 1414 keV had previously been reported as a 1400 keV double transition by Horen and Kelly, and as a 1390 keV double transition by Dostrovsky et al. To obtain a more accurate energy measurement of the 1395 and 1414 keV one would require a large volume detector with slightly better resolution than the one available. The 1395 and 1405 keV gamma rays are accommodated by the decay scheme of Horen and Kelly, but the 1414 keV gamma ray is not.

Figure 3-2(b) gives the energy spectrum between 1500 and 2000 keV as recorded by the large co-axial detector. The 1556 keV transition is barely discernable and the energy and intensity measurements have considerably less accuracy than is usual.

The range between 1585 and 1854 keV in Figure 3-2(b) contains several compton shoulders which almost resemble energy peaks in a Ge(Li) spectrum.

The 1941 keV transition is almost completely masked over by the Compton edge of the 2171 keV gamma ray. However, distinct evidence of a true 1941 keV transition is given by the presence of a Compton edge at 1716 keV.

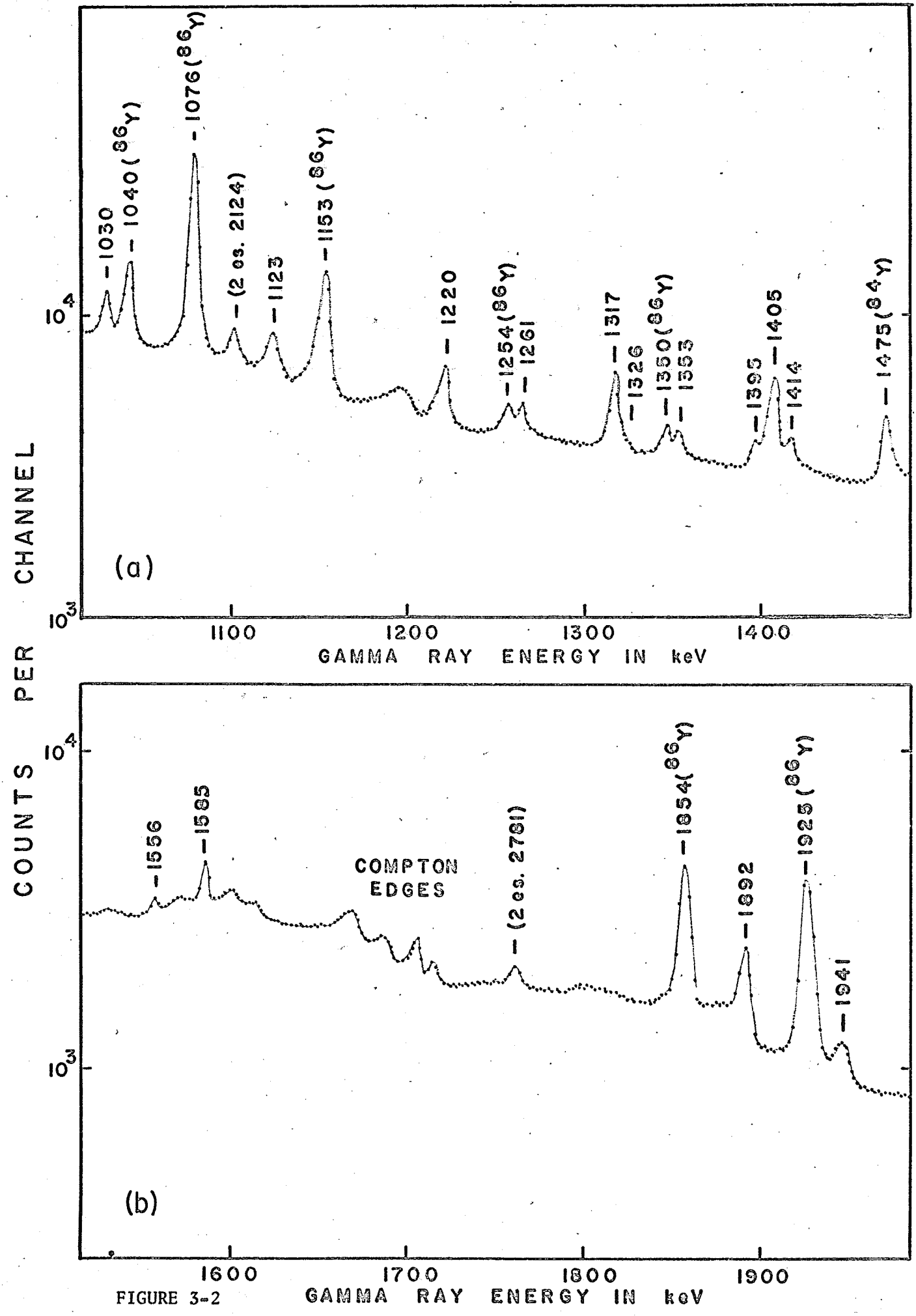

COUNTS PER CHANNEL
10⁴
10³
1030
1040(86Y)
1076(86Y)
(2 es. 2124)
1123
1153(86Y)
1220
1254(86Y)
1261
1317
1326
1350(86Y)
1353
1395
1405
1414
1475(84Y)
(a)
1100
1200
1300
1400
GAMMA RAY ENERGY IN keV
1556
1585
COMPTON EDGES
(2 es. 2781)
1854(86Y)
1892
1925(86Y)
1941
(b)
1600
1700
1800
1900
GAMMA RAY ENERGY IN keV

FIGURE 3-2

Figures 3-3(a) and 3-3(b) show the spectrum obtained from the balance of the energy region that was scanned in this study. Figure 3-3(a) shows the region between 2000 and 2500 keV in which there are three gamma rays belonging to ^{85}Y decay. Figure 3-3(b) shows the region between 2500 and 3000 keV which contains four gamma rays that are due to the de-excitation of ^{85}Sr levels. The 3009 keV transition was observed only during an extended period of counting on the large detector and even then it was only vaguely discernable. A half-life could not be assigned to it due to the lack of statistics, and for the present must be accepted on faith from Horen and Kelly as 4.7 hr.

A complete summary of the gamma-rays observed in the de-excitation of levels in ^{85}Sr is given in Tables 3-1 and 3-2 along with a comparison of previous work in this field. The energies in Tables 3-1(a) and 3-1(b) attributed to the present work are estimated to be accurate within ±0.5 keV.

Tables 3-2(a) and 3-2(b) give a comparison of the relative intensities obtained in the present work with those reported previously by others. The energies listed are those obtained in the present work and the intensities of Horen and Kelly are from their equivalent transitions. Most of the intensity measurements listed for the present work are estimated to be accurate to within about 10%.

Of this, approximately 3% is due to the detector efficiency measurements with the balance being due to statistics and the corresponding error in obtaining the background. Peaks with very poor statistics have a considerably larger inaccuracy.

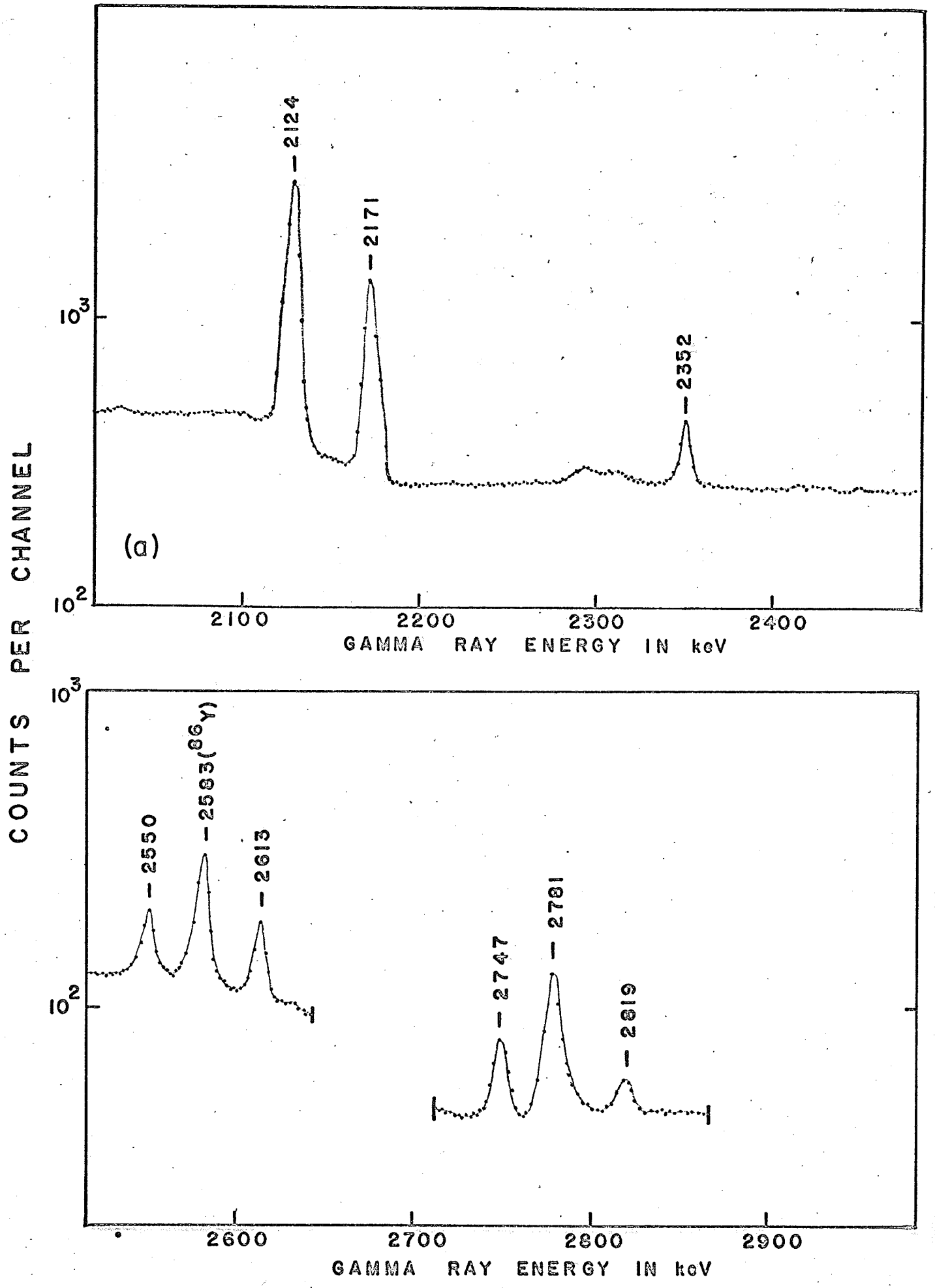

2124
2171
2352
10^3
10^2
(a)
2100
2200
2300
2400
GAMMA RAY ENERGY IN keV
COUNTS PER CHANNEL
2550
2583(^{86}Y)
2613
2747
2781
2819
10^3
10^2
2600
2700
2800
2900
GAMMA RAY ENERGY IN keV

FIGURE 3-3

TABLE 3-1 (a)

GAMMA RAY ENERGIES ^{85}Y

Present Work	Horen 1966	Dostrovsky 1963	Patro 1962
231.1	231	231	225
		510	233
536.2	540		530
(539.2)			
547.3			
554.3	550		
569.2	571		
612.5	614		
617.3	614		
700.0	699	700	
726	724		
767.7	769	772	
787.2	789		
(801.9)			
818.5	816		
861.0	862		
1029.8	1032	1030	
1122.8	1123	1130	
1220.8	1223	1230	
1261.4	1263		1250
1317.3	1323		

TABLE 3-1 (b)

GAMMA RAY ENERGIES ^{85}Y

Present Work	Horen 1966	Dostrovsky 1963	Patro 1962
1326	1326		
1353.1	1353		
1394.8		1390	
1404.6	1400		
1414.2			
1557.1	1556		
1585.5	1580	1590	
1892.3	1888	1870	
1941.0	1939		
2123.5	2120		
2171.4	2169	2160	
2351.7	2350	2340	
2549.5	2550		
2747	2745	2750	
2781	2779		
2819	2812		
(3009)	3009		

TABLE 3-2 (a)

GAMMA RAY RELATIVE INTENSITIES ^{85}Y

Energy (keV)	Present Work	Horen 1966
231.1		33.6
536.2	2.69	3.5
539.2	-	-
547.3	1.04	-
554.3	-	0.32
569.2	1.33	0.47
612.5	1.02	0.84
617.3	1.0	1.1
700.0	1.2	1.1
726	0.37	0.33
767.7	4.7	4.7
787.2	1.3	1.4
801.9	-	-
818.5	1.0	1.1
861.0	0.69	1.4
1029.8	2.19	2.1
1122.8	1.41	1.8
1220.8	1.73	1.7
1261.4	0.51	0.67
1317.3	-	-
1326	-	0.97

TABLE 3-2 (b)

GAMMA RAY RELATIVE INTENSITIES ^{85}Y

Energy (keV)	Present Work	Horen 1966
1353.1	0.55	0.27
1394.8	0.50	-
1404.6	3.25	3.7
1414.2	0.50	-
1557.1	0.19	0.19
1585.5	1.89	1.3
1892.3	1.58	1.2
1941.0	0.60	0.74
2123.5	4.09	4.47
2171.4	2.13	2.0
2351.7	0.44	0.50
2549.5	0.11	0.19
2747	-	-
2781	0.39	0.37
2819	0.13	0.36
3009	-	0.3

TABLE 3-3

GAMMA RAY ENERGIES ^{85m}Y

Present Work	Horen 1966	Dostrovsky 1963	Patro 1962
231.1	231		
(235.5)			
237.7	237		
504.5	503		
		510	
740.8			730
913.4	915	925	920

3.2 Coincidence Measurements

Due to the complexity of the spectrum, the only coincidence measurements, with any real meaning, that were possible with the present NaI(Tl) - Ge(Li) system were with the 231 keV transition.

The energy range covered during these coincidence measurements was from 0 up to 2500 keV. The net coincidence spectrum with the 231 keV transition is shown in Figure 3-4. This was determined by making the appropriate corrections to the 'peak true' spectrum as explained in Chapter II. Table 3-4 gives a list of the transitions in coincidence with γ-231.

The results from the coincidence measurements support the existing decay scheme of Horen and Kelly (Horen 1966), with the addition of the 1317.3 keV transition in coincidence with γ-231.

Also present in the coincidence spectrum are four gamma rays from ^{86}Y decay. These transitions were in coincidence with the 252 keV transition in ^{86}Sr which, due to the poor resolution in the NaI(Tl) detector, was included in the energy window.

3.3. Discussion

Theoretical calculations for the energy levels, spins and parities of ^{85}Sr have been made by Talmi and Unna (Talmi 1960). They considered the first 38 protons and neutrons as forming closed shells and then limited their treatment to neutron configurations with exactly 38 protons. Their

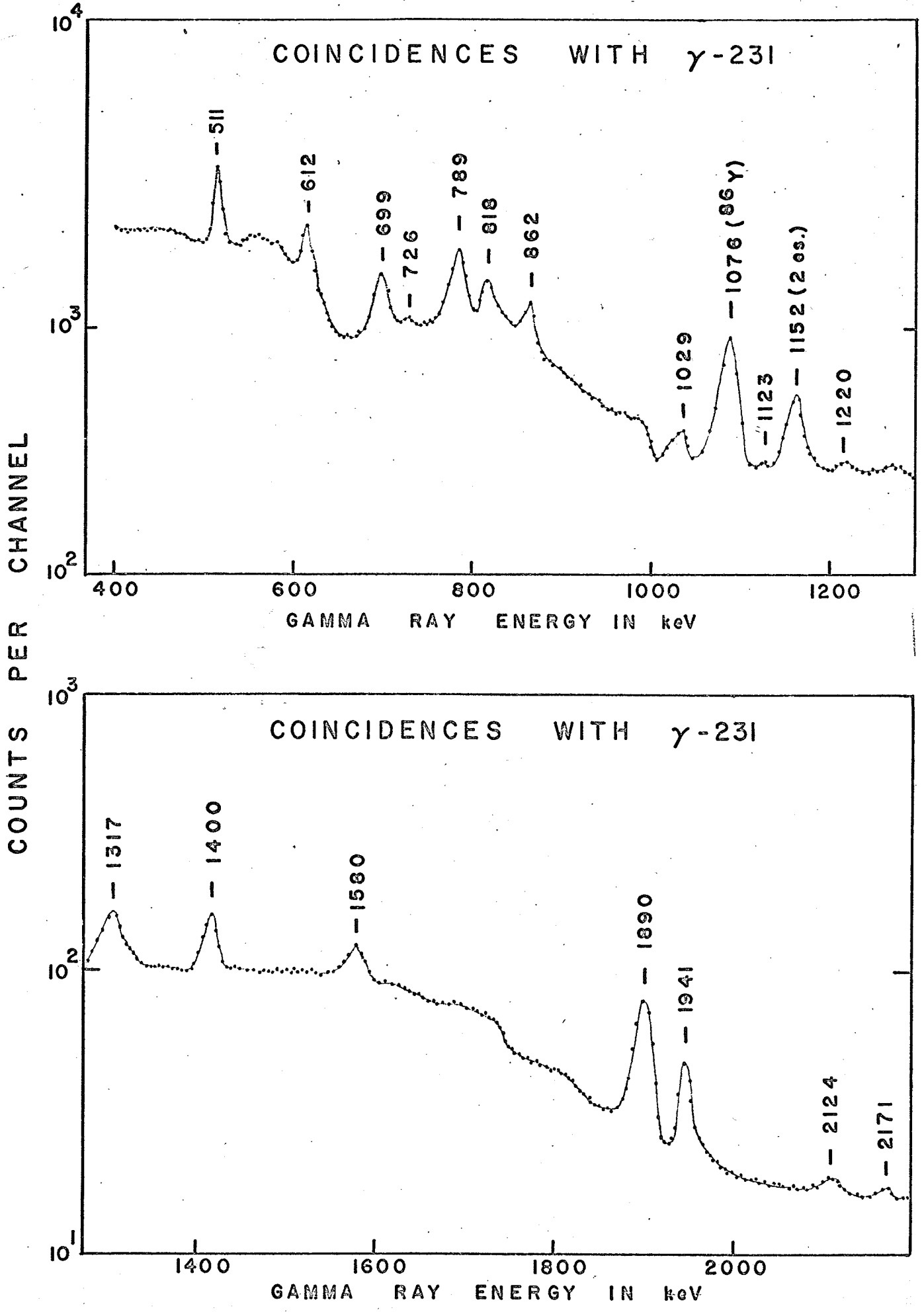

COINCIDENCES WITH γ-231
COUNTS PER CHANNEL
GAMMA RAY ENERGY IN keV
511
612
699
726
789
818
862
1029
1076 (86γ)
1123
1152 (2 es.)
1220
COINCIDENCES WITH γ-231
1317
1400
1580
1890
1941
2124
2171

FIGURE 3-4

TABLE 3-4 (a)

COINCIDENCE GAMMA RAYS WITH γ-231

Energy (keV)	Remarks
511	MoC^2 Annihilation
536.2	Not resolved in coincidence spectrum
539.2	
547.3	
554.3	
569.2	
612.5	Not resolved in coincidence spectrum ^{86}Y
617.3	
646	
700.0	
726	
787.2	
818.5	
861.0	
1029.8	
1078	^{86}Y
1122.8	
1153	^{86}Y

TABLE 3-4 (b)

COINCIDENCE GAMMA RAYS WITH γ-231

Energy (keV)	Remarks
1220.8	
1317.3	Not resolved in coincidence
1326	spectrum
1394.8	Not resolved in coincidence
1404.6	spectrum
1585.5	
1857	^{86}Y
1892.3	Agrees with Horen 1966
1941.0	Agrees with Horen 1966
2123.5	

subsequent calculations were for even parity levels in Sr^{85} which can be formed with $(g_{9/2})^{-3}$ and $(p_{1/2})^{-2}(g_{9/2})^{-1}$ neutron configurations. A comparison of the calculated levels and those reported experimentally is given in Figure 3-7. The diagram is self-explanatory and there appear to be considerably more levels reported experimentally than are theoretically predicted. This means that the theoretical model proposed by Talmi and Unna is incomplete and needs to be modified.

The transitions in ^{85}Sr observed in this study are basically in agreement with those reported by Horen and Kelly (Horen 1966) who performed a fairly intensive study of the decay of ^{85}Y and ^{85m}Y. However, with the use of higher resolution detectors it was possible to separate three doublets and one triplet.

The decay schemes proposed on the basis of the present work are virtually the same as those of Horen and Kelly. The major change is due to slightly different energy measurements and also the resolving of three doublets and a triplet.

The proposed energy levels in ^{85}Sr populated by the decay of 2.9 hr. ^{85m}Y are shown in Figure 3-5. This is in agreement with the existing scheme of Horen and Kelly although the levels have a slightly different energy. There were however two extra gamma rays with 2.9 hr. activity observed in this study. They have energies of 235.5 and 740.8 keV If these are a result of transitions in ^{85}Sr they could be accommodated by the introduction of a new level at 978.5 as illustrated by the dotted lines in Figure 3-5. This level is partially supported by a theoretical prediction

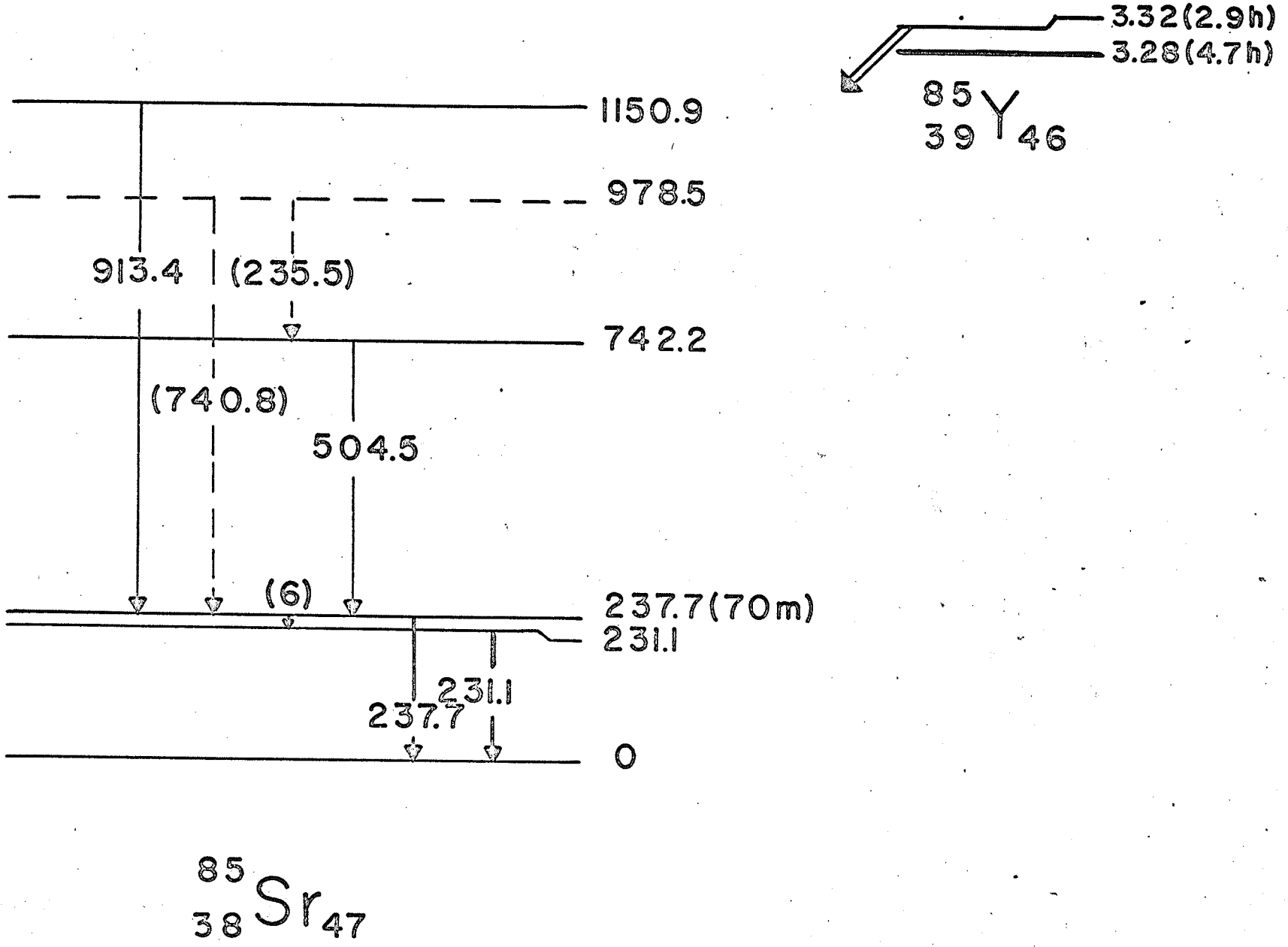

3.32(2.9h)
3.28(4.7h)
85 39 Y 46
1150.9
978.5
913.4
(235.5)
742.2
(740.8)
504.5
(6)
237.7(70m)
231.1
231.1
237.7
0
85 38 Sr 47

FIGURE 3-5

of a level at 970 keV. This fact however is quite meager support due to the poor comparison of other experimental and theoretical levels, and this level must be considered as quite hypothetical.

The proposed energy levels in ^{85}Sr populated by the decay of 4.7 hr.^{85} Y are shown in Figure 3-6. This also is basically in agreement with the existing decay scheme of Horen and Kelly, although once again the energies of some levels have been changed slightly. The major change is due to the separation of the 614 and 1400 keV peaks. With the exception of the 1414 keV gamma ray, the resolved doublets were easily accommodated by the existing decay scheme in an unchanged position.

Horen and Kelly did not assign the 2747, 2819 and 3009 keV transitions to the decay scheme. If a level at 2819 were to exist, the 1414 and 1405 keV transitions could be combined to form a cascade from this level. This however would require the introduction of another level at either 1405 or 1414 keV, the former level being preferred due to intensity considerations. Once again, these levels must be considered as extremely hypothetical and are based mainly on cascade considerations.

Horen and Kelly also proposed a tentative level at 802 keV. During an extended period of accumulation, a very weak transition at 801.9 keV was observed. This could possibly be the transition to ground of the 802 keV level, but it was too weak to obtain a lifetime measurement on it. Also, the sum of the 554.3 and 569.2 keV photons are within a kilovolt of the 1122.8 keV transition, which might suggest that these two photons form a cascade from the 1353 keV level to the 231 keV level. Thus, on the

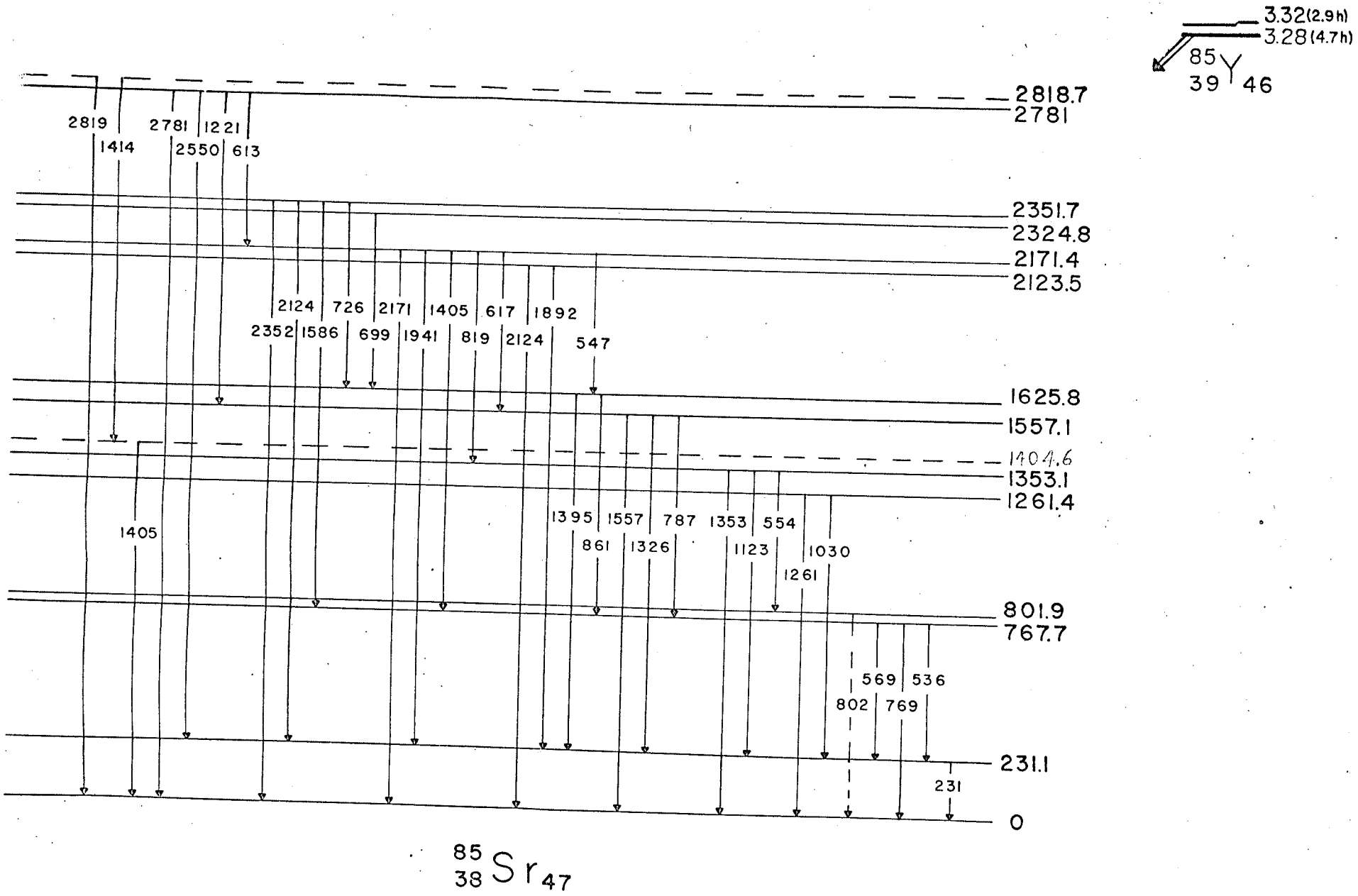

3.32(2.9h)
3.28(4.7h)
85 Y
39 46
2818.7
2781
2351.7
2324.8
2171.4
2123.5
1625.8
1557.1
1404.6
1353.1
1261.4
801.9
767.7
231.1
0
2819
1414
2781
2550
1221
613
2124
2352
726
1586
699
2171
1941
1405
819
617
2124
1892
547
1405
1395
861
1557
1326
787
1353
1123
554
1261
1030
569
802
769
536
231
85 Sr 47
38

FIGURE 3-6

^{85}Sr ENERGY LEVELS

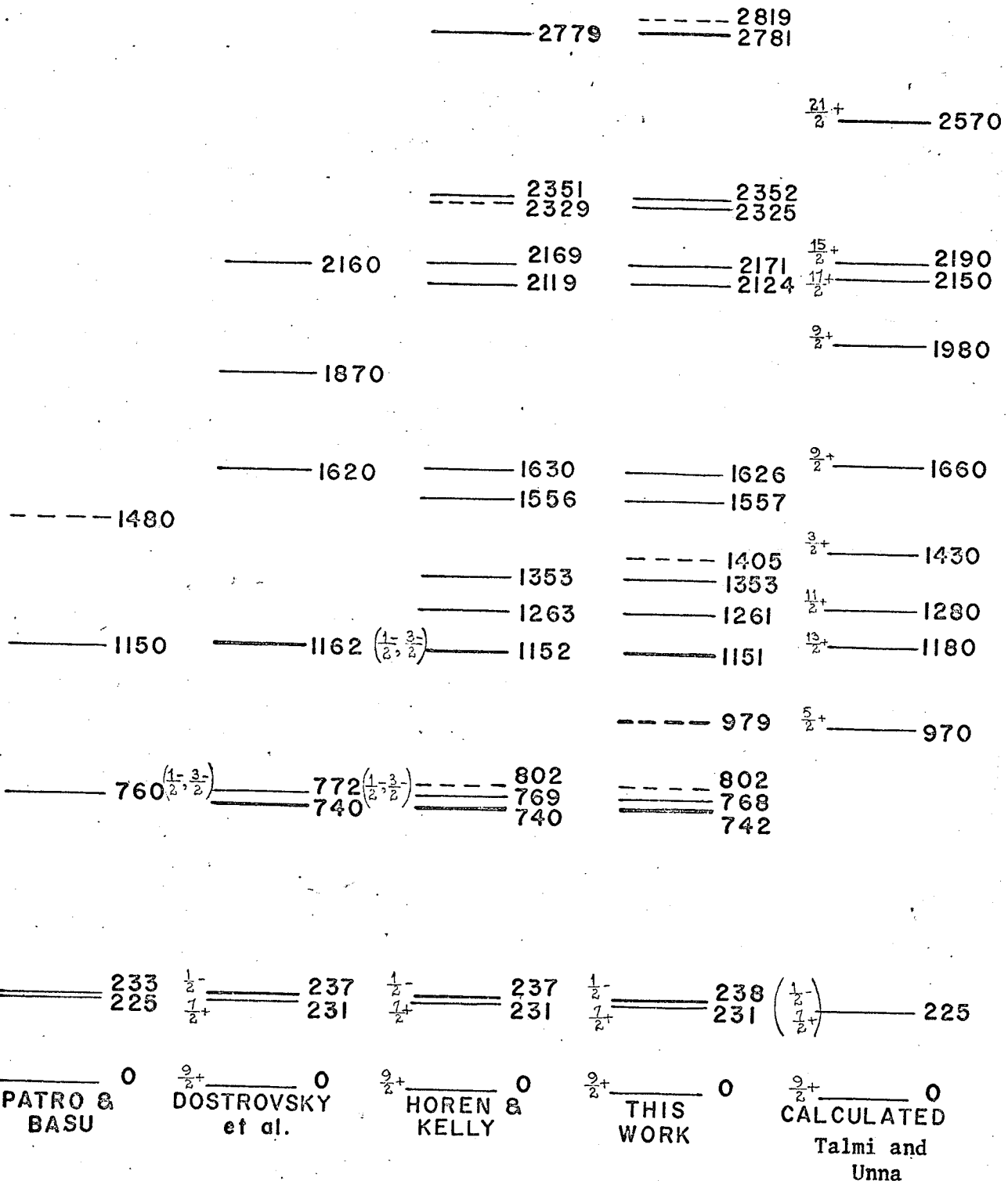


FIGURE 3-7

basis of the above cascade plus the evidence of the 801.9 keV transition, support is given to Horen and Kelly's proposed level at 802 keV, although a coincidence experiment at this energy would be very helpful.

The newly separated transition at 547 keV has tentatively been placed between the 2171 and 1626 keV levels solely on energy considerations.

A fairly intense peak at 1317 keV was observed (Figure 3-2(a)) during all runs and had a half-life of about 5 hr. This gamma ray can not be accommodated by the existing decay scheme and was not reported in previous work. However the spectrum of Horen and Kelly (Horen 1966) contains an 'equivalent' gamma ray listed as 1323 keV which they subsequently mention nothing about. In its place they adopted a 1326 keV transition of lower intensity, which fits the decay scheme and in the present study is listed as a possible transition appearing on the shoulder of the 1317 keV photo peak.

The 1317 keV gamma ray was also found to be in coincidence with the 231 keV transition (Table 3-4). In order to determine the exact placement and/or the validity of this gamma ray, one would require more complete coincidence data with two Ge(Li) detectors.

The decay scheme proposed in the present study is basically in agreement with that proposed by Horen and Kelly (Horen 1966), with the changes as noted above. In order to further clarify the decay scheme one would require two large volume high resolution Ge(Li) detectors. One could then carry out the much more accurate Ge(Li) - Ge(Li) coincidence measurements and remove existing ambiguities or uncertanties.

REFERENCES

Barker, P. H. and Connor, R. D., 1967 Nucl. Inst. and Methods 57, 147

Brown, R. A., 1968 Ph.D. Thesis, University of Manitoba

Caretto, A. A. and Wiig, E. O. 1952 J. Am. Chem. Soc. 74, 5235

Dostrovsky, I., Katcoff, S., and Stoenner, R. W. 1963 Phys. Rev. 132 2600

Evans, R. D. 1955 The Atomic Nucleus

Freck, D. V. and Wakefield, J. 1962 Nature 93, 669

Haverfield, A. J. 1966 Thesis University of California, Berkeley UCRL - 16969

Hollander, J. M., Lederer, C. M. and Perlman, I. 1967 Table of Isotopes, sixth edition

Horen, D. J. and Kelly, W. H. 1962 Bull. Am. Phys. Soc. 7, 341

Horen, D. J. and Kelly, W. H. 1966 Phys. Rev. 145, 988

Maxia, V., Kelly, W. H. and Horen, D. J. 1962 J. Inor. Nucl. Chem. 24, 1175

Patro, A. P. and Basu, B. 1962 Nucl. Phys. 37, 272

Talmi, I. and Unna, I. 1960 Nucl. Phys. 19, 225

Tavendale, A. J. 1966 I.E.E.E. Trans. Nucl. Sci. NS-13 No. 3, 315

Wanio, K. M. 1965 Thesis University of Michigan