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THE USE OF A SOLID STATE DETECTOR FOR CONVERSION ELECTRON SPECTROSCOPY AND A STUDY OF THE RADIOACTIVE DECAY OF $^{97}$Ru

DISSERTATION

Presented in Partial Fulfillment of the Requirements for the Degree Doctor of Philosophy in the Graduate School of The Ohio State University

By

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PUBLICATIONS


Atkins, M. C. and Gillespie, C. M.; "Reentry Vehicle Composites"; FOR 1853; July 1964 (Report S-RD).


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INTRODUCTION

Over the past few years a new and powerful tool has become available to the low energy nuclear spectroscopist—the solid state or semiconductor detector. While it offers no fundamentally new capability, the improvement over previous detectors is so great that whole new areas of research are opened up; and many of the earlier experiments can be profitably repeated. Of the several types of solid state detectors, by far the most useful are the lithium drifted silicon (Si(Li)) and lithium drifted germanium (Ge(Li)) types. Until quite recently most of the work involving such detectors was concerned with the detectors themselves (and the necessary low-noise preamplifiers and amplifiers). While their manufacture is still partly an art, there are now a number of commercial sources for solid state detectors; and a rapidly increasing number of papers are appearing where such detectors have been employed. An excellent review of solid state detectors and some of their applications has been given by Hollander (1).

To get an idea of the impact of solid state detectors, consider the goals of the nuclear spectroscopist. Leaving aside reasons stemming from practical applications or from the desire to simply obtain new or better numbers, the major motivation for research on nuclear decay schemes is to provide data to aid in the development of nuclear structure theory. Actually models might be
a better word. Several models based on experimental data have been
developed, but no theoretical understanding such as that for the
atomic regime has been achieved as yet. Of the many quantities
describing a particular nucleus perhaps the most basic are the
angular momentum (spin), parity and half-life of each level, and
the energies of the excited levels relative to the ground level.
The branching among various competing decay modes in the decay of
a parent nucleus and the transition probabilities between levels
in the daughter nucleus are also of interest. These quantities
depend on processes occurring within the nucleus and on the spin
and parity of the levels involved.

The lower lying excited levels in many nuclei are populated
in the radioactive decay of some parent nucleus. To unravel a
radioactive decay and assign spin and parity, a wide variety of
experimental techniques are usually required. The energy levels
can frequently be determined from either gamma-ray or conversion
electron spectroscopy. However, if a transition is highly con­
verted, it can be undetected with gamma-ray techniques; and if
weakly converted, it may be obscured in the conversion electron
spectra. Determination of branching ratios requires knowledge of
both gamma-ray and conversion electron relative intensities and at
least one conversion coefficient. Coincidences among the various
emissions are frequently necessary to help establish the level
scheme, and gamma-gamma coincidence measurements are routinely
employed. Delayed coincidence measurements not only yield the
half-life of excited levels, but can tell the proper order of
levels. Gamma-electron or electron-electron coincidences can be of similar value, but relatively few groups are equipped to perform such measurements.

Once a level scheme has been determined a variety of techniques are available to help decide the spin and parity of the levels. One of the most reliable and most frequently employed is a measurement of the internal conversion coefficients or the ratio of these coefficients for the various electron shells and subshells. Comparison of the experimental value with the theoretical predictions for each transition frequently allows the multipolarity of the transition to be unambiguously determined. Finally, if the spin and parity of one of the levels (usually the ground level) is known, then the other values can be assigned relative to it.

(Direct measurement of ground state spin and parity is a complete area of research in itself and employs methods different from those under consideration here.)

This brief discussion points out the need for both gamma-ray and electron spectroscopy to arrive at a complete, definitive decay scheme. For many years the spectroscopist has relied primarily on the sodium iodide scintillation spectrometer for gamma rays and on a wide variety of magnetic electron spectrometers. The Ge(Li) detector is a direct replacement for the scintillation detector for many purposes. Its principal advantage is its several-fold improvement in resolution over almost the entire energy range of interest in low energy nuclear spectroscopy. For complex spectra it easily gives information which can be obtained from scintillation
detectors, if at all, only with the aid of laborious and less accurate unscrambling techniques. Virtually the only remaining advantages of the scintillation detector are its greater efficiency and the background of experience in its use. As techniques for making larger Ge(Li) detectors are developed and experience is gained in their use, both these advantages may disappear. The fact that Ge(Li) detectors must be cooled to liquid nitrogen temperature is not a great drawback for most laboratory uses. The Si(Li) detector, with its lower atomic number compared to the Ge(Li) detector, is primarily used for electron detection. Its low sensitivity to gamma rays is mostly a nuisance but perhaps can be put to some use.

The Si(Li) detector may prove as valuable to the spectroscopist as the Ge(Li) detector, but for slightly different reasons. It does not replace but rather competes with various magnetic electron spectrometers. (Scintillation detectors for electrons using organic solids and solutions have been available for many years but because of poor resolution and other difficulties have been little used. Proportional counters have proved useful but in rather specialized areas.) There is such a wide variety of magnetic spectrometers that a comparison with the Si(Li) detector is difficult. Furthermore, the rapid advance in solid state detectors and in particular the associated electronics makes a comparison based on today's capability invalid in a short time. In general, compared to the Si(Li) system described here, magnetic spectrometers have comparable to far better resolution depending on the particular
instrument and the way it is adjusted. The solid state detector will usually have greater solid angle (or transmission) and can be used with fairly large sources. A most significant difference is in the fact that the solid state detector records the entire spectrum simultaneously while the magnetic spectrometer records each individual point in the spectrum sequentially. This last difference is removed in the case of magnetic spectrographs; however, obtaining quantitative information on intensities from these is a difficult and tedious job, and some of the advantage of simultaneous recording is lost because of the lesser sensitivity of photographic plates compared to electronic recording.

Choice between the Si(Li) and the magnetic spectrometer for the study of conversion electrons thus involves considerations of the complexity of the spectrum, the half-life and amount of activity available, and other factors such as the difficulty of background subtraction. With the Si(Li) detector, when more than one transition is present the lower energy peak is superimposed on the background from the higher energy electrons which are back-scattered out of the detector with only partial energy loss. The Compton background from gamma rays may also be a problem unless it can be subtracted out. None of these are present in the magnetic spectrometer.

The considerations just given all have to do with the physics of the situation, but there is another aspect which has nothing to do with the physics. Magnetic spectrometers, particularly the modern, high transmission types, are sophisticated and
expensive instruments. Many groups with a capability for gamma-ray spectroscopy do not have a complimentary capability for electrons. (The converse is, of course, also true.) This places a rather arbitrary restriction on the scope of their ability which may now be easily removed by the Si(Li) detector. The detector and necessary electronics are comparatively inexpensive and are used with the same multichannel analyzer used for gamma-ray spectroscopy. With modest equipment it is possible to obtain not only electron energy spectra but conversion ratios and conversion coefficients with an accuracy superior to some methods currently in use. Beyond this basic capability there are the new possibilities for such things as coincidence and angular correlation work with electrons where the advantages of the solid state detectors may be more decisive, but these are beyond the scope of this discussion.

This dissertation is divided into two parts. Part I discusses the development of instrumentation and experimental techniques for conversion electron spectroscopy with a Si(Li) detector. Chapter I discusses design criteria for the spectrometer and the mechanical and electronic components of the completed instrument. Chapter II is concerned with calibration standards. Chapter III discusses the performance of the spectrometer in terms of those quantities which determine its capability as an experimental tool. Chapters IV and V consider experimental techniques for the measurement of conversion ratios and conversion coefficients respectively. The techniques developed are tested and calibrated by measurements on the calibration standards.
Part II (Chapter VI) is an experimental study of the decay of $^{97}$Ru. Here several experimental approaches are employed—conversion electron spectroscopy among them. The emphasis here is almost entirely on the experimental data and its interpretation rather than upon the experimental techniques. The preceding discussion on the need for data on both gamma rays and conversion electrons is well illustrated in this study.
PART I

DEVELOPMENT OF INSTRUMENTATION AND EXPERIMENTAL

TECHNIQUES FOR CONVERSION ELECTRON SPECTROSCOPY
Since Si(Li) detectors are still quite new and are just beginning to be applied as research tools, there are no "standard" designs for spectrometers employing them. In scintillation gamma-ray spectroscopy there are more or less standard designs for various purposes, and for one particular design a catalogue (2) of gamma-ray spectra obtained with it is now in its second edition. This situation will probably come about for solid state detectors of both types but only after their applications are more thoroughly explored, their characteristics more standardized, and their ultimate performance capability more nearly achieved. This chapter presents, in order, the design criteria for the mechanical components of an electron spectrometer, a description of the resulting hardware, the operating procedures, a description of the mechanical features of the detector, the general features of the electronics, and finally, the selection of the detector bias.

Design criteria

The Si(Li) detector may be operated at either room temperature or cooled and does not require storage at low temperatures as do Ge(Li) detectors. Cooling significantly reduces the electronic noise generated in the detector and improves the resolution by
almost a factor of two with the electronics employed here. The best temperature for cooled operation according to Hollander (1) is in the range of -50° to -80°C. Since the resolution at room temperature is sufficient for some purposes, it was desired that the system be capable of operating at either room temperature or dry ice temperature (-78°C). In the following discussion the term cooled will be used specifically to mean operation at dry ice temperature.

Solid state detectors are extremely sensitive to moisture; and since the detector used here is not hermetically sealed, the requirement for cooled operation also requires that the detector be operated in vacuum. Independent of this, vacuum operation is required to minimize air scattering and energy loss. A vacuum of a few microns was thought to be adequate to prevent significant condensation and is more than adequate to eliminate air scattering and energy loss. The detector is light sensitive so the vacuum chamber must be light tight.

Among other things, the resolution is dependent on the input capacitance to the preamplifiers. With resolution measured as the full width at half maximum (FWHM) in keV of a monoenergetic peak, the increase in resolution from increased input capacitance is roughly 0.1 keV/picofarad. Coaxial cable such as RG 71B/U which might be used to connect detector and preamplifier has a capacity of about 1 picofarad per inch and BNC connectors each have a capacity of several picofarads. It is thus clearly desirable to place the preamplifier close to the detector and eliminate as much of this input capacity as possible.
The count rate will vary widely from source to source and from one particular source as the activity decays. To obtain good counting statistics in a reasonable time under these conditions it is necessary that the source to detector distance be variable. Incremental spacing through the range of 1 to 10 cm was thus specified. With the detector diameter of 1 cm this gives solid angles for axial point sources ranging from 5.3 to 0.063% of the total sphere. The spacings must be accurately known and reproducible.

The requirements for cooling, minimum detector-preamplifier distance, and variable source-detector distance all point to a system in which the detector is fixed in the vacuum system and the source position is variable. However, this approach was rejected because of the additional requirement that the detector be capable of operating in coincidence with gamma-ray detectors available in the laboratory. These other detectors would be outside the vacuum system for the Si(Li) detector and view the source through a thin window. For gamma-gamma coincidence counting it is usually desirable to have both detectors equally distant from the source. For electron-gamma coincidence counting this is not necessarily the case since the detectors are not both looking at the same radiation. For maximum flexibility then the source-detector spacing for both detectors must be variable. After considering various ways of achieving this, it seemed most desirable to have the detector position variable with respect to the vacuum system and source, although the spectrometer construction and operation
would not be as simple as for the fixed detector arrangement. Another constraint arose because of the physical lay-out of the existing Ge(Li) gamma-ray detector. In order to position the coincidence source closer than several inches from the detector, the lower part of the vacuum system containing the source must not exceed a diameter of 3.4 in. (assuming axial symmetry).

For mounting sources, standard aluminum rings comparable with the various gamma detectors already in use in the laboratory were chosen. These rings are 2.13 in. outside diameter, 1.50 in. inside diameter, and 0.031 in. thick.

Backscattered electrons and electrons ejected by gamma absorption are a source of undesirable background. To minimize this, low-Z material should be used for all surfaces visible to the detector.

The final criterion was simplicity. Ideas such as an air lock to speed sample changes when operating cooled, and a system for circulating alcohol from a dry ice cold bath were considered but rejected. A more sophisticated system could readily be designed allowing faster and easier operation; but at this early stage in the use of Si(Li) detectors, and with improvements occurring so rapidly, it seemed wise not to invest too heavily at first and to learn from a simple system how best to design better systems.

Description of mechanical components

The final design of the mechanical components is shown approximately full scale in Figure 1. Non-essential features have
Fig. 1. Cross section drawing of spectrometer. Non-essential features omitted and clearances exaggerated for clarity. A source detector spacing of 1 cm is illustrated.
been eliminated and clearances exaggerated for clarity. All parts with the exception of the cylindrical steel can of the vacuum system were fabricated in the Physics Graduate Student Shop.

The central stainless steel piston houses the detector on its lower end and has the preamplifier rigidly attached to its top end with four screws passing through the nylon bushing. This arrangement allows the detector to be coupled directly into the preamplifier through a hole in the bottom of the chassis. The originally provided BNC connector has been removed. The preamplifier thus moves with the detector as the source-detector spacing is varied. Although normally the back end of the preamplifier is supported, no harm results from cantilevering its entire weight from the piston. The detector bias (and output signal) is carried by the central lead passing through the Kovar seal to the collector terminal of a standard TO5 transistor socket into which the detector is plugged. The base and emitter terminals are grounded to the piston. Ground continuity is completed to the preamplifier chassis by a steel screw passing through the nylon bushing. Access to the transistor socket leads is through a half inch diameter hole milled through the piston wall. The detector flange is held against the end of the piston by a spring washer which is lightly compressed when the brass collar is screwed tight. The washer is made of 0.005 in. shim stock and prevents any great stress from being applied to the detector.

Detector cooling is achieved by placing crushed dry ice on the brass plate up to the bottom of the nylon bushing. Thus the entire brass plate, o-ring assembly, and the top of the piston
are held at dry ice temperature. Thermal contact with the detector is through the length of the piston. Stainless steel is a poor choice for a "cold finger" as far as thermal conductivity is concerned. It was chosen because the piston must be resistant to dents, scratches, and corrosion, if a durable sliding vacuum seal is to be achieved. A polyurethane foam dam and lid contain and insulate the dry ice. The entire assembly is supported from the bottom of the brass plate which is insulated with waterproof cardboard. The nylon bushing thermally insulates the preamplifier from the piston. The chrome plated steel vacuum can which is silver soldered to the brass plate has a thin (1/32 in.) wall except for the lower portion and proves quite effective in impeding "cold flow" down the can. Frost forms on the upper 2 to 3 in. but no further. The thermal gradient is so steep down the can that only on the most humid day does any unfrozen condensate form. The 0.014 in. window in the aluminum end plate remains dry except on the most humid days.

When cooled to dry ice temperature the buna-n o-ring is frozen, and there was initially concern about whether the vacuum seal would be maintained under these conditions. It was found that a grease-free seal would occasionally develop a leak, but that greasing the o-ring with Dow Corning Silicone High Vacuum Grease prevents this and even allows the piston to be rotated and moved up and down while cooled without breaking the seal. (Note, however, that the system was not designed to be moved while under vacuum. If accidentally released, the piston is sucked in, and
its sudden stop may damage the detector or other components.) A special o-ring with lower temperature capability has thus not been necessary.

The detector-preamplifier is a high impedance system so the bias lead must be well insulated from ground. The Kovar seal is cooled along with the detector, and there was concern that condensation on the atmospheric side could short out the bias lead. To prevent this, a "spaghetti" sleeve around the bias lead was run from the Kovar seal up into the preamplifier chassis. The inside of the spaghetti was potted with Dow Corning Silastic RTV 891 silicones rubber on its lower end, and additional rubber was used to seal the outside of the spaghetti to the porcelain part of the Kovar. No moisture problems have been encountered.

Access to the system for changing sources is through the aluminum end plate. It is held in place by three studs with wing nuts and vacuum seal is by a rubber gasket. Compression for the vacuum seal is provided mainly by the vacuum, and the wing nuts need only be finger snug. The sample may be mounted directly on the end plate or on a plexiglas platform (not shown in Figure 1) which raises it approximately 3 cm higher. In either position the sample is held in place by two spring clips which also provide source grounding to the end plate. When the platform is used, it is screwed to the end plate. Incrementally variable source-detector spacing is obtained with a series of copper spaces which are slipped around the piston and determine the distance between the top shoulder of the piston and the top of the o-ring.
compression nut. The spacers are made from 1 in. streamline copper tubing with a lengthwise strip cut out. The strip removed is slightly less than half the circumference so the spacers snap into place snugly around the piston. Table 1 gives the source-detector spacing for each spacer for the two source positions, along with an estimate of the maximum possible error.

Reproducible geometry in rotation about the symmetry axis is provided by painted or scribed alignment marks for appropriate components.

For some purposes it is desirable to absorb the electrons from a source and observe only the gamma rays. To permit this an aluminum collar and flange is slipped over the lower end of the piston and held in place just above the brass collar with a set screw. Two nylon screws extending downward from the flange to below the detector surface mate with a plexiglas holder into which the appropriate number of Be or Al absorber discs may be inserted. This arrangement holds the absorbers against the front of the detector housing and about 1 mm from the detector window. The length of the nylon screws is adjusted so they just clear the source mounting ring when the nominal 1 cm source-detector spacing is used (for either source position). The plexiglas holder is in place only when absorbers are required.

Two steps have been taken to minimize the background from electrons scattered into the detector. A Be disc of 1.5 in. diameter has been glued over the window of the end plate, and two sheets of 0.04 in. thick polyethylene have been placed over the steel inner wall of the vacuum can.
TABLE 1. Source-detector separation and solid angle subtended by front surface of sensitive volume of detector for axial point source

<table>
<thead>
<tr>
<th>Spacer</th>
<th>Source on End Plate Separation (cm)</th>
<th>Solid Angle (Percentage of Total Sphere)</th>
<th>Source on 3 cm (Nominal) Platform Separation (cm)</th>
<th>Solid Angle (Percentage of Total Sphere)</th>
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<tbody>
<tr>
<td>None</td>
<td>0.32</td>
<td>23.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>0.93</td>
<td>6.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>1.41</td>
<td>2.92</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>1.92</td>
<td>1.61</td>
<td></td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>2.90</td>
<td>0.72</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>3.91</td>
<td>0.409</td>
<td>0.95</td>
<td>5.7</td>
</tr>
<tr>
<td>F</td>
<td>4.91</td>
<td>0.260</td>
<td>1.95</td>
<td>1.56</td>
</tr>
<tr>
<td>G</td>
<td>5.92</td>
<td>0.180</td>
<td>2.95</td>
<td>0.70</td>
</tr>
<tr>
<td>H</td>
<td>6.90</td>
<td>0.132</td>
<td>3.93</td>
<td>0.405</td>
</tr>
<tr>
<td>I</td>
<td>9.89</td>
<td>0.064</td>
<td>6.93</td>
<td>0.131</td>
</tr>
</tbody>
</table>

a Estimated maximum possible error 0.03 cm.
b Estimated maximum possible error 0.04 cm.

A Welch Duo-Seal Vacuum pump is used and with the system well out-gassed a pressure of 1 micron or less is reached. A thermocouple vacuum gage is located on the pumping line close to the vacuum chamber. The pumping speed is high, and normally the system reaches 10 microns in about two minutes. If the system has been open to the atmosphere for some time, a longer time is required to reach 10 microns; however, when not in use, the system is normally left under vacuum.
Operating procedures

For operation at room temperature the spectrometer is quite simple and easy to use. Assuming a spectrum has just been recorded, the following procedure is used to change sources and record another spectrum.

1. The bias voltage is reduced to zero at the power supply.
2. The valve at the vacuum pump intake is closed. The pump is not turned off.
3. Air is admitted to the system and the relief valve closed as soon as atmospheric pressure is reached.
4. The end plate, with sample, is removed and the new sample substituted. Care should be taken that the spring clips are making contact, and the sample is properly positioned in rotation.
5. Any change in source-detector geometry or addition of absorbers is made, being careful that the detector and source are not damaged through incorrect choice of spacer. Note that when the absorber holder is in position a source-detector spacing of less than 1 cm (nominal) must not be attempted.
6. The end plate is replaced, and the vacuum pump intake valve slowly opened to the full open position.
7. When the thermocouple gauge indicates a vacuum of better than 100 microns, the bias voltage is applied and data may be taken.

For operation at dry ice temperature two additional steps are required. If the system is cold from previous use, step 0. and step 8. are included in the above sequence of steps.
0. Remove the foam insulation and remaining dry ice. For rapid warm-up direct warm air from a hair dryer onto the exposed part of the piston. When spacer E (see Table 1) is used, the dryer should stay on for about eight minutes. Less time is required for longer spacers, more for shorter. After the dryer is turned off, observe the increase in dead time as the detector warms up. When it reaches the previous room temperature reading, or ceases to increase, wait one or two minutes to insure the detector is above the dew point, then go to step 1.

8. After step 7, place the foam insulator around the brass plate and fill with crushed dry ice to the bottom of the nylon bushing. Put the foam cover on. Observe the decrease in dead time; and when it reaches the previous cold reading or ceases to drop, data may be taken. Normally the dry ice should be checked and replenished if necessary about 60 min after the initial cooling and about every 100 min thereafter.

Steps 0, and 8, assume the analyzer sensitivity is adjusted so that the increase in detector noise at room temperature over that cooled contributes at least an additional 10% to the dead time. In most situations this would be desired since cooling the detector decreases the low energy noise cutoff, and the sensitivity must be increased to accept the low energy data pulses.

The detector

The detector is a Model W-80-2AA, Serial Number 0547, purchased from Technical Measurements Corporation (TMC), San Mateo, California. The nominal specifications on the size of the sensitive
volume are: thickness 0.2 cm and diameter 1 cm. The detector (Serial Number 0547) was measured by TMC and found to have a depleted region thickness of \(0.216 \pm 0.003\) cm and diameter of \(1.021 \pm 0.003\) cm. A sketch of the Si crystal in the detector is shown in Figure 2. The external configuration of the steel case of the detector is shown in Figure 1. A standard T05 transistor base is used for the electrical contacts. The base and emitter terminals are grounded to the detector housing, and the collector terminal supplies the bias. The entrance window is stated by TMC to consist of less than one-half micron of p-type silicon and a gold layer 500 Angstroms thick. The gold layer is grounded to the detector housing. Recommended operating voltage is between 100 and 300 volts positive bias. Leakage current at 200 volts bias and room temperature was measured by TMC and found to be 0.42 microamps.

The detector described above is the second one used in this work. The gold window of the first window was damaged by mercury and its performance degraded. The performance of the two detectors appears to be identical. However, in no case has a calibration for the first detector been assumed to apply to the second although such a procedure would appear to be justified.

**Electronics**

The preamplifier is a Tennelec Instrument Company, Model 100B. It is a charge sensitive, vacuum tube, low noise instrument designed for use with Si(Li) detectors. Commonly the preamplifier output goes to a main amplifier which in turn feeds the multichannel
Fig. 2. Cross section drawing of Si crystal in detector.
analyzer. Several main amplifiers designed particularly for work with solid state detectors are available. In addition to having low noise these main amplifiers have provisions for front panel adjustment of the pulse shape. This pulse shaping is essential to obtain best resolution from the system. The output of the detector has a rise time on the order of 0.1 microseconds which is the time required to collect the electron-hole pairs produced by an ionizing radiation. If the rise time of the system is faster than this, it increases the bandwidth for noise without affecting the signal thus decreasing the signal-to-noise ratio.

These main amplifiers are rather expensive, and it was decided to see if satisfactory performance could be achieved without one. Here the preamplifier output would be fed directly to the multichannel analyzer, and the analyzer amplifier used close to maximum gain. This approach was successful in the case of a gamma-ray spectrometer using a Ge(Li) detector and a similar preamplifier (3). Since the preamplifier, as received, did not include pulse shaping, it was necessary to make this modification. Using the $^{137}$Cs K-conversion line as a standard, the rise and fall times were varied in the range of 0.1 to 1 microsecond. It was found that a rise time of 0.2 microsecond and a fall time of 0.3 microsecond produced the minimum resolution. The minimum was fairly broad, and the above values were not critical. With the 0.2 microsecond rise and 0.3 microsecond fall time the resolution was quite close to that specified for the preamplifier, so no further effort was made to improve the resolution through pulse shaping.
In the above work it was necessary to operate the analyzer at its highest gain even with the $^{137}$Cs K-conversion line which is of comparatively high energy. More gain was clearly desirable. The manufacturer states that the Model 100B gain may be increased by a factor of ten by simply decreasing the feedback of one amplifier stage. The full factor of ten did not appear necessary, and it was feared that this great an increase might unnecessarily degrade the stability. A factor of five was thus chosen. In both pulse shaping and gain modifications the replacement components were all low temperature coefficient parts.

A Tennelec Model 901RM preamplifier power and detector bias supply was used. The detector bias supply is capable of supplying up to 200 volts positive bias and is adjusted by means of a single turn potentiometer.

The multichannel analyzer for all the work here was a Radiation Instruments Development Laboratory (RIDL), Model 34-12B. It is a 400-channel instrument with memory capacity of $10^5$ counts/channel and is equipped with typewriter, plotter, and magnetic tape output. All counting times reported here are live times.

**Selections of detector bias**

The detector bias is known to affect both the resolution and the detector output although no quantitative data on this have been found. For low bias voltage greater recombination of the initial ionization occurs, reducing the output signal and adversely affecting the resolution. As the voltage is increased, recombination is decreased since the electrons and holes are separated more
rapidly, but the leakage current is increased. As the leakage current increases, the resolution (FWHM) increases. As the bias is increased, one might thus expect to find a minimum in resolution and a decreasing slope to the curve of output versus bias. The latter finding could occur if the charge collection approached 100% within the bias range investigated.

To investigate this effect the bias voltage was varied between 100 and 300 volts in 25-volt increments. Up to 200 volts the internal bias supply in the power supply was used; from 200 to 300 volts an external battery and potentiometer was used. The detector was cooled and a spectrum of the K-conversion line of $^{137}$Cs was recorded at each bias. The resolution and channel number (to the nearest $1/10$ of a channel) into which the peak fell are shown in Figure 3. The results show that the resolution has a fairly broad minimum centered at 185 volts. The location of the peak—and thus detector output—does increase with bias voltage reaching its maximum at 250 volts. The slight decrease at 300 volts may or may not be real since peak locations may be in error by 0.2 channels, and the system is known to drift slightly.

The power supply is well regulated so the observed variation in peak location with bias is inconsequential; the bias may thus be chosen on the basis of resolution alone. Any value between 175 and 200 volts is satisfactory. Since 200 volts (the maximum output of the power supply) is conveniently and reproducibly set by turning the bias potentiometer to its stop, this value was chosen.
Fig. 3. Resolution and channel number of peak vs detector bias.
The original detector was used in this work. Because the present detector appears to be similar in all respects and because the resolution minimum is broad, it was not thought necessary to repeat the measurement. Resolution with the present detector is the same as the original.
CHAPTER II

CALIBRATION STANDARDS AND SOURCE PREPARATION

Calibration standards

Calibration standards are required to satisfy several criteria. Besides their use for energy calibration, they are a means for determining the system response to monoenergetic electrons. They also are used to calibrate the system for measurement of conversion coefficients. The standards, therefore, should give fairly uniform coverage in energy; should have simple, well understood spectra; should be readily available with high specific activity; and should have reasonably long half-lives.

The standards selected are listed in Table 2 along with pertinent data on their decay. All were purchased from the Isotopes Development Center, Oak Ridge National Laboratory, Oak Ridge, Tennessee. Data on x ray energies were taken from Siegbahn (4, Appendix VI). Gamma-ray energies are from the Nuclear Data Sheets (5). Since several energy values are given for each gamma ray, the chosen value is the one with the smallest quoted error or an average of those with the smallest error. Values of conversion electron energies are given for K-, L\textsubscript{II}-, and M\textsubscript{I}-shell conversion. However, these values do not necessarily represent the true energy loss in the detector. Necessary corrections will be discussed in the next section. Experimental values on conversion ratios
<table>
<thead>
<tr>
<th>Parent Nuclei</th>
<th>Half Life (d=days, y=years)</th>
<th>$K\alpha_1$ X ray Energy (keV)</th>
<th>Gamma-Ray Energy (keV)</th>
<th>Conversion Electron Energy (keV)</th>
<th>Conversion Ratio</th>
<th>Conversion Coefficient&lt;sup&gt;a&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{109}$Cd</td>
<td>470d</td>
<td>22.1</td>
<td>88.0</td>
<td>62.5 84.5 87.3</td>
<td>K/LM = 0.84</td>
<td>=11.5 (E3)</td>
</tr>
<tr>
<td>$^{114}$In</td>
<td>50d</td>
<td>24.2</td>
<td>190.9</td>
<td>163.0 187.0 190.1</td>
<td>K/LM = 1.02</td>
<td>=2.45 (E4)</td>
</tr>
<tr>
<td>$^{203}$Hg</td>
<td>47d</td>
<td>72.8</td>
<td>279.1</td>
<td>193.6 264.4 275.4</td>
<td>K/L = 3.33, L/(L_2: L_3 \approx 3:2:1)</td>
<td>=0.163</td>
</tr>
<tr>
<td>$^{113}$Sn</td>
<td>118d</td>
<td>24.2</td>
<td>392.8</td>
<td>364.9 388.9 392.0</td>
<td>K/LM = 4.2</td>
<td>=0.450 (M4)</td>
</tr>
<tr>
<td>$^{137}$Cs</td>
<td>30y</td>
<td>32.2</td>
<td>661.6</td>
<td>624.2 656.0 660.3</td>
<td>K/LM = 4.6</td>
<td>=0.094</td>
</tr>
</tbody>
</table>

<sup>a</sup>Values with multipolarity indicated are theoretical values from Rose (7).
including L-subshell ratios are from the Nuclear Data Sheets. These numbers are accurate to within a few percent as judged by the quoted errors on individual measurements and agreement between different measurements.

For conversion coefficients, listed in the last column of Table 2, the data are not as good. For $^{203}$Hg and $^{137}$Cs the measured coefficients are in good agreement, have small quoted error, and agree well with the theoretical values. For $^{109}$Cd the older data are generally 10 to 20% below the theoretical value. However, at least one recent measurement (6) employing current techniques obtained a value <2% below the theoretical value and has a claimed error of <4%. The value listed for $^{109}$Cd is the theoretical value from Rose (7). For $^{114}$In and $^{113}$Sn no recent measurements have been found. All measurements given in the Nuclear Data Sheets are below the theoretical values. The multipolarity for both transitions is well known; and since there seems to be a general tendency for the older conversion coefficient measurements to be low, the theoretical value for $\alpha_K$ from Rose is listed. The value of the total conversion coefficient for $^{114}$In and $^{113}$Sn has been computed from the theoretical value of $\alpha_K$ and the K/LM ratio given in column 8 of the table.

Window correction and location of multicomponent peaks

Two separate corrections must be applied to the data in Table 2 to obtain the proper energy for energy calibration purposes. The first is a correction on electron energy for energy loss in the
detector window. The second is to determine the average energy of a peak which is composed of more than one component as in the case of x rays and L-shell conversion electrons where the various L-shell components are not resolved.

Consider first the window correction. From Siegbahn (4, p. 11) the most probable energy loss, $\Delta E$ (MeV), for an electron passing through a thickness, $x$ (cm) of material may be written as

$$
\Delta E = ax[\ln \frac{mc^2 \beta^2 ax}{I^2(1 - \beta^2)} - \beta^2 + 1.12],
$$

where

$$
a = 0.153 \frac{\rho Z}{\Lambda \beta^2}.
$$

In this expression $\rho$ (gm cm$^{-3}$) is the density, $Z$ the atomic number, $\Lambda$ the atomic weight, $I$ (MeV) the mean excitation energy of the atomic electrons, $\beta$ the ratio of incident electron velocity to the velocity of light, and $mc^2 = 0.511$ MeV. Note that the most probable energy loss rather than the mean energy loss gives the quantity of interest here, that is, the shift in energy of the experimentally measured peak.

The detector window is composed of a silicon dead layer and a gold contact layer as discussed already. The zapon cover over the sample (discussed in the next section) may also be included as part of the window, and to simplify the calculation, it has been assumed to be made of carbon. The zapon covers are assumed to have a thickness of 30 microgram cm$^{-2}$. The calculated energy loss for each of these three components and their sum is shown in Figure 4.
Fig. 4. Most probable electron energy loss in detector window vs electron energy.
Consider now the case of a peak composed of two or more unresolved components. The experimentally measured peak is in a channel corresponding to some average of the energies of the various components. In the case of the K-x ray peak, four components make a significant contribution. In Siegbahn's notation these are $K\alpha_1$ (100), $K\alpha_2$ (50), $K\beta_1 + K\beta_3$ (35) and $K\beta_2$ (15) where the numbers in parentheses are the relative intensities. Actually the relative intensities are slightly dependent on $Z$; however, for purposes here the indicated strengths are sufficiently accurate. More detailed information on intensities is available in Wapstra (8).

The average peak energy for the K-x ray has been determined by graphically summing gaussian distributions with intensities weighed as above. In doing this the width of each component must be appropriate to the resolution of the system. A resolution of 6 keV (FWHM) has been assumed, but the results would not change significantly for a 1-keV variation about this value. Under these conditions it is found that the average peak energy is 0.4 keV greater than the $K\alpha_1$ x-ray energy. The same energy shift applies to both $^{109}\text{Cd}$ and $^{114}\text{In}$ because the energy differences between the components of $^{109}\text{Cd}$ and $^{114}\text{In}$ are very nearly the same.

The same summing procedure has been applied to the L-shell conversion peak for $^{203}\text{Hg}$ using the L-subshell conversion ratios given in Table 2. The resulting average peak energy is 264.2 keV which is 0.2 keV less than the $L_{II}$-subshell conversion electron energy. For all the other standards the energy difference between the L-subshells is much less than for Hg, and the summing correction
is not necessary. In these cases the $L$-peak energy is taken to be the average of the $L_I$- and $L_{III}$-subshell conversion electron energies.

Table 5 gives the energies for all useful calibration peaks after the corrections just discussed have been applied. The x ray and the $^{203}$Hg L-peak energies are specifically for the 6-keV (FWHM) resolution obtained with the detector cooled. However, for room temperature operation the same data may be used with negligible error. This is because the corrections are small and, as will be discussed in Chapter III, drift at room temperature is probably greater than the correction. Note that because of the window correction a calibration curve obtained with the corrected energies will be a curve for energy actually deposited in the detector. To determine the correct energy of an unknown conversion electron peak from this calibration curve, the window correction must be added to the energy read from the calibration curve. This prompts the question of why the window correction should be applied at all. The answer is that without correction the calibration curve would be nonlinear at low energy. Of course, above about 150 keV the correction is insignificant compared to other errors and is almost constant; so if the region of interest is above this energy, it does not matter whether or not the window correction is applied.

Source preparation

Source preparation for conversion electron spectroscopy is similar to that for beta-ray spectroscopy except in one respect.
TABLE 3. Energy of peaks from calibration standards after window correction and correction to obtain average energy of peaks with several components

<table>
<thead>
<tr>
<th>Parent Nuclei</th>
<th>X-Ray Energy (keV)</th>
<th>Gamma-Ray Energy (keV)</th>
<th>Conversion Line Energy (keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{109}$Cd</td>
<td>22.5</td>
<td>88.0</td>
<td>62.1 84.4 -</td>
</tr>
<tr>
<td>$^{114}$In</td>
<td>24.6</td>
<td>190.9</td>
<td>162.8 186.9 -</td>
</tr>
<tr>
<td>$^{203}$Hg</td>
<td>-</td>
<td>279.1</td>
<td>193.4 264.1 275.9</td>
</tr>
<tr>
<td>$^{113}$Sn</td>
<td>-</td>
<td>392.8</td>
<td>364.8 388.7 -</td>
</tr>
<tr>
<td>$^{137}$Cs</td>
<td>-</td>
<td>661.6</td>
<td>624.1 655.7 -</td>
</tr>
</tbody>
</table>

*a*Not useful for calibration because peak not resolved or not sufficiently intense.

Beta sources should be prepared on as thin a backing as possible to minimize scattering of electrons from the backing and the resulting distortion of the shape of the spectrum. For conversion electron spectroscopy this is less of a problem since the backscatter spectrum is smooth and may be subtracted from the line spectrum. Also, electrons backscattered out of the detector contribute a background at all energies below the incident electron energy so there is a background regardless of backing thickness. Nevertheless, the backing should be as thin as practical.

Source charging is a well-recognized problem in beta spectroscopy, but whether or not charging would be detectable with the instrumentation and source handling techniques here was not known. (The sources are not in the spectrometer for long periods
of time and tend to be discharged by the moisture in the air.) Some of the initial sources were thus prepared on a mylar backing, and detectable charging did occur. By comparison with sources prepared on aluminized mylar, charges on the order of a kilovolt were found. Subsequently all sources were prepared on aluminized mylar.

The thickness of the radioactive material itself is of greatest importance. A crude rule might be that if the radioactive material can be seen, even under a microscope, the source is too thick. This fairly ideal situation has not been achieved in many cases, but for all the calibration standards it has been closely approximated. In the case of the calibration standards, the radioactive material is present as a metallic salt dissolved in an acid. This must be placed on the aluminized mylar backing and dried. In the drying process the droplet tends first to contract as the volatile material is evaporated, and then the solids tend to form a few large crystals. The contraction makes the total area covered by the source smaller, and the formation of crystals makes the source nonuniform. One common way to alleviate this problem is to dry a small amount of protein, such as insulin, onto the backing before the sample is deposited. The protein acts as a wetting agent and more uniform sources result. A readily available source of protein, Knox Unflavored Gelatine, was tried. This gave satisfactory results, and therefore no other materials were experimented with.
All calibration standards were prepared in the same way. Aluminized mylar of total thickness 0.83 mg cm$^{-2}$ was glued to the aluminum rings already described with the aluminized side of the mylar next to the ring. Colloidal graphite (DAG) was found to be an excellent glue. In addition to insuring electrical contact, it stretches the backing uniformly and tightly as it dries. A drop or two of a solution of about 300 mg of Knox gelatine dissolved in 300 ml distilled water was placed in the center of the aluminized surface and dried. With light near grazing incidence the protein film may be observed and appears to be of fairly uniform thickness and without structure. Since the protein film might serve as an insulator, it was lightly scribed through in several places with a steel point. The radioactive material was then placed over the protein area, distributed as evenly as possible with the toothpick size sliver of aluminum foil used to transfer the material from shipping vial to sample, and dried. In some cases the acid in the radioactive material dissolved part of the aluminum layer on the mylar, thus the radioactive atoms were probably well mixed with both the protein layer and the aluminum salt thus formed. This undoubtedly made the sample thicker but not enough to be detectable. Using this method it is difficult to control the sample diameter accurately; however, it was possible to keep the great majority of radioactive material within a few millimeters of the center.

The final step was to place a cover over the sample to prevent even the slightest contamination of the detector. This is
important since the detector cannot be cleaned without danger, and a low background is essential for conversion coefficient measurement. Thin zapon foils were prepared in much the conventional way. One drop of undiluted zapon lacquer was dropped onto a water surface in a large beaker. The drop would spread to about two inches in diameter and could easily be lifted out on a wire frame. These foils were somewhat thicker than desired, as determined by carefully trimming the edges after drying on the wire frame and then weighing the foil of known area. A simple way of reducing the thickness was found. After the lacquer had spread on the water, two metal needles were placed close together on the edge of the foil and pulled apart. The foil would then spread to several times its original area, and after a few seconds of drying, could be lifted out. Several foils made in this averaged less than \( \approx 30 \text{ microgram cm}^{-2} \). Much thinner foils can be made, but for this application they would have no advantage and would offer less protection and containment to the sample.

The final step is to place the foil over the sample. The wire frame on which the foil is lifted from the water is circular and just fits inside the aluminum ring. After lifting, any foil which has folded over the frame, giving a double thickness, is wiped to the frame edge with a wet cotton swab. The foil is strong enough that this seldom damages it. The foil is then inverted and placed over the sample (e.g., the top of the floating foil contacts the sample). There is enough adhesion that when one
edge of the foil contacts the sample, the rest is pulled down without trapping air. The foil with wire frame attached is dried, and then the frame removed with the aid of a knife. Foils thus prepared have proved entirely satisfactory.
CHAPTER III

SPECTROMETER PERFORMANCE

In this chapter a number of factors relating to the operation of the complete system are discussed. These factors largely determine the experimental capability of the system. In the order of their discussion they are: resolution, linearity, drift, and background and noise.

Resolution

The resolution is defined as the full peak width in energy measured at half the maximum count rate of a monoenergetic peak. This is commonly referred to as the full width at half maximum (FWHM).

At dry ice temperature the resolution obtained for the K-conversion electron peaks of the five standards ranges between 5.6 and 6.4 keV, FWHM, with the higher value corresponding to the higher energy peaks. A slight increase in resolution with increasing energy is to be expected since the statistical uncertainty in the number of ion pairs increases as the square root of the energy. At room temperature the resolution ranges between 9 and 10 keV with the same general energy dependence. The pre-amplifier is equipped with input circuitry which allows test pulses to be supplied with a pulser while the detector is disconnected. In this way essentially noise-free pulses can be
input with very low input capacitance and the performance of the electronics alone measured. Resolution obtained in this manner is 4.5 to 5.0 keV and independent of input pulse height.

The resolution is the most commonly quoted and for most purposes the most important measure of a spectrometers capability. The better the resolution (smaller FWHM) the more complex the spectrum which can be investigated. But even where the resolution is not needed to resolve the various components of the spectrum, it is a major factor in determining the accuracy with which the spectrum can be studied. Consider an isolated peak which is very weak compared to the background. As the resolution is reduced, the number of channels into which the peak is distributed is also reduced, but the background is not changed. The number of counts in the peak is unchanged, but its height relative to the background is greater; thus its location and strength can be more accurately measured.

The decision as to whether or not to cool the detector in order to improve the resolution depends on the particular experimental situation. Appendixes I and II show spectra for all the calibration standards with the detector cooled and at room temperature.

Linearity

For maximum ease and accuracy in data analysis the energy calibration (e.g., energy vs channel number) should be linear. Nonlinearity can be corrected for in practice by using a precision pulser to obtain a curve of pulser peak location (channel number)
vs input pulse height and normalizing this curve to the location of conversion electron peaks of known energy. This is, of course, a tedious procedure and one to be avoided if possible. Unfortunately, the system described here is nonlinear, but in a puzzling way. In four energy calibration curves, each with the detector cooled and each at a different gain, the calibration curve is found to be quite linear up to about channel 250. Beyond channel 250 the curve is linear but has a lower value for its slope. As an example, in one of the calibrations the slope up to channel 250 was 0.767 keV/channel; above channel 250 it was 0.738 keV/channel. A pulser calibration curve obtained under the same conditions (detector cooled and not disconnected, but no source) and normalized to the calibration curve from the standards gave identical results. Calibration curves at other gains were similarly checked with the pulser and the same nonlinearity confirmed. Since the change in slope occurs at about the same channel for different gain settings and is the same for both calibration standards and pulser, it was suspected that the converter section of the analyzer was at fault. To check the linearity of the converter independent of the rest of the system, the pulser was input directly to the converter and the pulser peak location vs input pulse height measured. The converter was found to be linear to within the accuracy of the measurement, about 0.2 channels. The cause of the nonlinearity has not been pursued further. Perhaps it results from some subtle interaction among the various components of the system; but, in any event, with knowledge of the reproducible behavior of the nonlinearity, it can be corrected for.
In all the calibration curves measured thus far the maximum deviation of an individual point from the best line through all the points has been about 0.5 keV cooled and 1.0 keV at room temperature. It has also been found that at the same gain setting the cooled and room temperature curves do not exactly coincide. The maximum difference is about 1 keV, but there is insufficient data to draw further conclusions.

Drift

Drift, or the failure of the total system gain to remain constant, adversely affects both the resolution and the accuracy of the energy calibration. Extensive measurements of drift for this system have not been made because of the time required and because such data are not of great value other than to help decide what accuracy may be quoted on energy measurements. Enough data are available, however, to indicate the approximate magnitude of the drift under various circumstances. The drift is expressed in terms of the energy obtained by multiplying the shift in channel number by the calibration curve slope (keV/channel).

The stability appears to be better at dry ice temperature than at room temperature. Over a half to one hour period with the detector kept at dry ice temperature, the drift is less than 0.2 keV. This is based on a number of pairs of identical, consecutive spectra recorded to check for drift. Over longer periods and at room temperature the drift may be as great as 1 keV. In a series of 7 consecutive spectra recorded over a 10-hour period the peak location (channel number) was observed to decrease to a
minimum and then increase. The maximum variation about the mean was slightly under 1 keV. Further information on drift is available from the calibration curves. If the deviation of the individual points used to construct the calibration curve from the best curve through all the points is interpreted as drift about the mean, then the drift is less than 0.5 keV cooled and 1 keV at room temperature. Several hours are required to obtain a calibration curve at dry ice temperature, and the system is cycled between room temperature and dry ice temperature five times. Of course, this is not a true measure of drift. The calibration points were taken in order of increasing (or decreasing) energy, thus a uniform rate of drift would be undetectable; but at least it gives an indication of what to expect.

In the case of two spectra having large live times, one of 10 hours live time, the resolution with the detector cooled was not different from spectra accumulated in only a few minutes. This provides additional evidence that in cooled operation the drift is less than a few tenths of a kiloelectron volt. Any slow drift greater than this would almost surely have been detected as an increase in resolution. In one spectrum accumulated in 6 hours live time at room temperature, the resolution was increased by about 0.4 keV over that for a comparable spectrum of short live time, again indicating that the drift at room temperature is greater than when cooled.
Background and noise

The background count rate for the spectrometer is low enough that for most work it may be neglected. It is important, however, to know what the normal background is and to monitor it regularly. Slight contamination of the detector or vacuum chamber is difficult to detect except in a background measurement but could cause significant error in a conversion coefficient measurement. The background is also a sensitive indicator of noise pickup from external sources.

Figure 5 shows a typical background accumulated in 1000 min at room temperature. Note that the ordinate is the number of counts per 1000 min per kiloelectron volt. For energies greater than $E_n$, the background is independent of detector temperature. For energies less than $E_n$, the count rate increases rapidly. These counts are from noise generated in the detector and preamplifier, and they set a lower limit on the useful energy range of the system. Any peak whose energy is less than about one FWHM greater in energy than $E_n$ will begin to merge with the noise, making quantitative analysis uncertain. The energy $E_n$ is dependent on the operating temperature. At room temperature it is about 21 keV and cooled it is about 15 keV. Thus the lowest energy electrons or x rays which can be studied without some loss of accuracy is about 30 keV at room temperature and 20 keV cooled. These limits might be lowered by subtracting the noise background, but it would first be necessary to show that the background is reproducible.
Fig. 5. Spectrometer background at room temperature.
Considerable difficulty has been encountered with external noise pickup leading to spurious counts. Tests have shown that such noise is picked up both from the power line and from direct radiation. Each noise source has its own characteristic energy spectrum (as recorded by the 400-channel analyzer). Some give an increase in the overall background, others have broad peaks, and some look very much like conversion electron peaks. The count rate also varies, and the noise may be continuous or intermittent. Efforts have been made to reduce the external noise pickup sensitivity of the system using various line filters and grounding arrangements with particular attention to ground loops, but they have not been successful.

The presence of external noise is frequently observable as an abnormal counting pattern on the real time scope display or as an abnormal fluctuation of the dead time, but a background spectrum is the most sensitive means of detecting such noise. Once detected, the source can usually be located and appropriate action taken. Several noise sources have been identified by either audible noise or brightly flashing lights which seem to frequently accompany the electrical noise.
The measured conversion ratio can sometimes be used to assign the multipolarity to a transition by comparison of the measured value with theoretical predictions for the various multipolarities. Whether or not this is the case depends on the accuracy of the measured ratio and the separation between the theoretical ratios for the various multipolarities. In this chapter the measurement of conversion ratios will be discussed, and conversion ratios for the calibration standards, as measured here, will be compared with the best known values. This comparison will help establish the accuracy with which conversion ratios can be measured. Realistic experimental error limits are necessary in deciding whether or not a multipolarity assignment is possible on the basis of a measured conversion ratio. First, however, the problem of determining the background of a peak will be considered.

**Background construction**

The term background, as used here, means the number of counts in a conversion electron peak not caused by conversion electrons losing all their energy in the detector. Defined thus, the background is composed of two components. One is the continuous background which would be present even if the conversion
electrons from the transition of interest were not present. The continuous background is composed of counts from beta rays and electrons from higher energy conversion peaks which, for one of several reasons, lose only a part of their initial energy in the detector. Counts from gamma rays are assumed to be negligible or to have been subtracted out. The second component is conversion electrons from the transition of interest which are backscattered out of the detector without complete energy loss.

If a monoenergetic beam of electrons is incident on a detector, the energy (pulse height) spectrum from the detector will be approximately as shown in Figure 6. The spectrum is composed of two components: a peak, assumed to be Gaussian, corresponding to those electrons which lose all their energy in the detector; and a tail extending from the peak back to zero energy and corresponding to those electrons which are backscattered out of the detector before losing all their energy. The dashed lines in Figure 6 show separation of the total spectrum into these two components. Since the system has finite resolution, some of the backscattered electrons which lose almost all their energy in the detector are recorded as counts under the full energy loss peak. These counts constitute a background which should not be included as part of the net number of counts in the peak. The exact shape of the backscattered electron tail extending under the peak is not known; but, even if it were, it would be tedious to have to construct the tail for each background subtraction. A simple approximation to the true background is given by the line AB in
Fig. 6. Approximate energy (pulse height) spectrum from a Li(Si) detector for incident mono-energetic electrons.
Figure 6. The abscissa of point B is the mean energy of the peak, and point A is located on the total spectrum where the peak joins the background. If the peak of interest is superimposed on the background from higher energy peaks or beta rays, the procedure is similar. The background from higher energies is simply extended back to give the baseline on which point B is located. A definite rule for locating point A has not been formulated. In most of the spectra encountered thus far there has not been much question as to its proper location. The point selected has usually been lower in energy than point B by about three times the FWHM.

Other techniques for constructing the background have been considered, but the one just described appears to be the best. It corresponds closely to what is actually taking place in the detector and is consistent with the definition of the peak-to-total ratio given later in this section. The technique described also tends to minimize the error in the net counts from incorrect location of point A.

A difficulty arises in the case of two peaks close enough together that the background between them cannot be determined. This situation occurs for the K- and L-shell plus M-shell conversion electron peaks (hereafter called the K-peak, LM-peak, etc.) over a wide range of intermediate atomic numbers and for the L- and M-peaks at high atomic numbers. The point A for the lower energy peak and B for the higher energy peak can be located as before. The problem is to find the background at the point B' for the lower energy peak. At point A the sum of the back-
scattering counts for the two peaks is just the difference in counts between points A and B (assuming the other component of the background is flat). The ratio of the backscattering component from the lower energy conversion electrons to that from the higher energy conversion electrons is approximately the same as the ratio of the peak counts of the lower energy peak to the peak counts of the higher energy peak. The backscattering component of the total background for the lower energy peak may thus be determined, and from it the total background for both peaks constructed. A minor refinement on this procedure is to guess the background in advance and subtract it before taking the ratio of the peak count rates. If the two peaks are superimposed on a sloping background, the necessary modifications to the procedure are obvious.

The peak-to-total ratio, \( d \), as defined here for a Si(Li) detector, is the ratio of the number of incident monoenergetic electrons which lose all their energy in the detector sensitive volume to the total number of such electrons incident on the detector sensitive volume. Then \( d = 1 - p \), where \( p \) is the backscattering coefficient defined as the number of backscattered electrons divided by the number of incident electrons. Discussion of the properties of backscattered electrons are given in Siegbahn (4, Chapter I) and by Steinberg (9). The value of \( p \) is independent of energy but depends strongly on \( Z \). The value of \( p \) for Si is not well known, but \( p = 0.23 \) is in fair agreement with all data found and will be used here. With this value, \( d = 0.77 \).
Since the peak-to-total ratio is independent of energy the number of counts in the backscattering tail for a given number of incident electrons is also independent of energy. As the energy of incident electrons decreases, then the count rate per unit energy in the backscatter spectrum must increase; thus the ratio of the count rate at point A to that at the peak becomes a function of the peak energy. In the procedure given for finding the background between two closely spaced peaks there is the implicit assumption that this ratio is the same for both peaks. If the separation of the peaks is small compared to their energy, then little error results; but if, for example, the two peaks had energies of 30 and 45 keV, a significant error results. To correct for this, the ratio of the backscattering components of the background may be multiplied by the ratio of the peak energies in the obvious way.

Conversion ratios

Consider now the calculation of the K/LM conversion ratio for the calibration standards other than supine Hg. The first step is to construct the background and obtain the net counts under the K- and LM-peaks. Denote these by $n_K$ and $n_{LM}$ respectively. The K/LM ratio is $N_K/N_{LM}$, where $N_K$ and $N_{LM}$ are the total number of conversion electrons emitted by the source from the K-shell and the L-shell plus the M-shell respectively. Now for every K-conversion electron there is coincident with it either a K-x ray or an Auger electron. There is thus some probability that the K-conversion electron and the x ray or Auger electron will both be detected,
resulting in a sum count in the LM-peak. It is convenient at this point to assume the K-shell fluorescent yield, $\omega_K$, is unity. The modification needed to remove this assumption will be given later. Taking into account the summing, the relation between $n_K$ and $N_K$ is

$$n_K = N_K \Omega d (1 - \Omega f_K)$$

(1)

where $\Omega$ is the solid angle subtended by the detector, d is the peak-to-total ratio, and $f_K$ is the probability that an x-ray entering the detector is completely absorbed. The probability that a K-conversion electron enters, and loses all its energy in, the detector is $\Omega d$, and the probability that the x-ray which accompanies each K-conversion electron is not detected is $(1 - \Omega f_K)$. The product $\Omega d (1 - \Omega f_K)$ is thus the probability that the K-conversion electron alone loses all its energy in the detector. The net counts in the K-peak are then just the total number of K-conversion electrons emitted by the sources times the latter probability. The net counts in the LM-peak are

$$n_{LM} = N_{LM} \Omega d + N_K \Omega d (\Omega f_K)$$

(2)

This equation assumes that an L- or M-conversion electron cannot be summed out of the LM-peak because of the resolution. The second term is the number of counts in the LM-peak from K-conversion electrons summing with K-x rays. Equations (1) and (2) may be solved for $N_K$ and $N_{LM}$ and the K/LM ratio written as
Equation (3) applies to all the calibration standards except $^{203}$Hg. For each of these the conversion electrons are emitted in a transition from an isomeric level to the ground level, and there is only one coincident K-x ray to sum with the K-conversion electron. If the upper level of the transition of interest decays promptly after being populated, then there is at least one other radiation in coincidence with the conversion electron. One example of this will be discussed later when $^{203}$Hg is considered.

In Equation (3),

$$f_K = 1 - e^{-1.06 \mu \rho x}$$

where $\mu$ is the photoelectric absorption coefficient of Si for the energy of the K$\alpha_1$ x ray, $\rho$ the density of the Si in the detector (the value 2.33 g cm$^{-3}$ is quoted by the manufacturer), and $x$ is the detector thickness. The coefficient 1.06 in the exponential is a correction to give the average path length through the detector for an axial point source at 1 cm distance. Actually $f_K$ should be slightly larger than the value given by Equation (4) because of multiple processes leading to complete absorption, but the error is not great. For the higher energy x ray where this error is greatest the summing correction is less significant.
Equation (3) applies to all the calibration standards containing $^{203}$Hg. For each of these the conversion electrons are in a transition from an isomeric level to the ground level, and there is only one coincident K-x ray to sum with the K-conversion electron. If the upper level of the transition of interest decays within after being populated, then there is at least one other transition in coincidence with the conversion electron. One example will be discussed later when $^{203}$Hg is considered.

In Equation (3),

$$f_K = 1 - e^{-1.06 \mu \rho x}$$  \hspace{1cm} (4)

where $\mu$ is the photoelectric absorption coefficient of Si for the energy of the K$\alpha_1$ x ray, $\rho$ the density of the Si in the detector (a value 2.33 g cm$^{-3}$ is quoted by the manufacturer), and $x$ is the detector thickness. The coefficient 1.06 in the exponential is a correction to give the average path length through the detector for an axial point source at 1 cm distance. Actually $f_K$ will be slightly larger than the value given by Equation (4) because of multiple processes leading to complete absorption, but the error is not great. For the higher energy x ray where this error is greatest the summing correction is less significant.
To remove the assumption that $\omega_K = 1$, $f_K$ in Equation (3) should be replaced by the expression

$$\omega_K f_K + (1 - \omega_K) d.$$  \hspace{1cm} (5)

This is just the sum of the emission probability times the detection probability for the two competing emissions. Note that in deriving Equation (3) and expression (5) summing with only the x ray or Auger electron involved in filling the K-shell vacancy has been included. The radiation from higher shells does not have sufficient energy to move a count from the K- to the LM-peak.

The conversion ratio calculation for $^{203}\text{Hg}$ is more complex. From the spectrum shown in Figure 16 it is seen that with the detector cooled the L- and MN-peaks are sufficiently resolved that both K/L and L/MN ratios may be derived. In this case it is simpler to calculate, in order, $N_K$, $N_L$, and $N_{MN}$ rather than derive single expressions for K/L and L/MN. The equation for $n_K$ is

$$n_K = N_K \Omega d (1 - \Omega d)[1 - \Omega(\lambda f_1 + \lambda f_2 + \lambda \omega_L f_3)]$$ \hspace{1cm} (6)

The term $(1 - \Omega d)$ is the probability that the K-conversion electron does not sum with the beta ray with which it is coincident.

The expression for the probability that an x ray is not detected is more complicated than before since the energies of the various competing x rays are sufficiently different that they may not all be approximated by the K\(\alpha_1\) energy. The x rays, including those from L-shell vacancies, have been divided into three groups as indicated by the subscripts on the $f$'s. The average energy for
each group has been taken to be the energy of the strongest component. On the basis of this grouping the statistical weight for each \( f \) is determined. The energy, statistical weight, and included x rays (in Siegbahn's notation) are: Group 1, 73 keV, \( \frac{1}{2} \), K\( \alpha_1 \), K\( \alpha_2 \); Group 2, 83 keV, \( \frac{1}{3} \), K\( \beta_1 \), K\( \beta_2 \), K\( \beta_3 \); Group 3, 10 keV, \( \frac{1}{4} \), all L-x rays. In deriving Equation (6) it was assumed that \( \omega_K = 1 \).

The equations for \( n_L \) and \( n_{MN} \) are:

\[
\begin{align*}
    n_L &= N_L \Omega d(1 - \Omega d)(1 - \omega_L \Omega f_3) \\
    &+ N_K \Omega d(1 - \Omega d)(\frac{1}{2} \omega_L \Omega f_3)(1 - \frac{1}{2} \omega_L \Omega f_3); \\
    n_{MN} &= N_{MN} \Omega d(1 - \Omega d) + N_K \Omega d(1 - \Omega d)(\frac{1}{3} \omega_L \Omega f_2) \\
    &+ N_L \Omega d(1 - \Omega d)(\omega_L \Omega f_3).
\end{align*}
\]

The explanation for each term will not be given since all the essential arguments have already been given. In Equations (6)-(8) it has been assumed that summing with L-series Auger electrons may be neglected on the grounds that these electrons do not have enough energy to move a conversion electron out of the peak in which it belongs. The detailed justification of this assumption is tedious, so only the essential points are outlined. The energy which must be added to an L-conversion electron to give a count in the MN-peak is roughly 10 keV, or about the energy of the L-series x ray. The average L-series Auger electron has less energy than
this by several kiloelectron volts. In penetrating the detector window these electrons lose at least another 2 keV. The result is that the majority of the Auger electrons do not deposit sufficient energy in the detector sensitive volume to cause an L-conversion electron to be counted in the MN-peak (or to move a K-conversion electron count out of the K-peak).

Equations (6)-(8) may now be solved for \( N_K, N_L, \) and \( N_{MN} \) in terms of the experimental values for \( n_K, n_L, \) and \( n_{MN} \). Of the other quantities appearing, only \( \omega_L \) is not well known. Actually there is a different fluorescence yield for each L-subshell so the correct value for \( \omega_L \) depends on the population of holes in the subshells. In Equations (6)-(8), \( \omega_L \) was used to represent two different modes of producing holes in the L-subshells; L-shell conversion and transitions of L-electrons to holes in the K-shell. Numerical data on L-shell fluorescent yields and Coster-Kronig yields are summarized by Wapstra (8). Consideration of this data leads to the conclusion that the initial difference in population of holes will be substantially erased by Coster-Kronig transitions, and that one is justified in using a single value of \( \omega_L \) in the two cases. The value of \( \omega_L \) is approximately 0.40. Fortunately the results for \(^{203}\text{Hg}\) are not sensitive to the value of \( \omega_L \).

The conversion ratios for the five calibration standards have been calculated using the techniques and theory just discussed. Conversion electron spectra were recorded for a 1 cm (nominal) source to detector spacing (source on end plate) and with the detector cooled. Appendix I contains work sheets showing
the conversion electron spectra and the details of the conversion ratio calculation for each calibration standard. The background assumed for each peak and the values of all parameters are given. The results are summarized in Table 4. The second column gives the experimental value obtained in Appendix I and the third column gives the percentage difference between the experimental value and the value from column 8, Table 2. To show the significance of the correction for summing the values of $n_K/n_{LM}$, etc., are given in column 4.

The errors for all six conversion ratios are small. The only trend is for the values to be slightly low. It seems reasonable to expect that conversion ratios can be measured to an accuracy of $\pm 10\%$ or better when the peak-to-background ratio and peak separation is as great as that for the $^{203}$Hg L- and MN-peaks. The results confirm the soundness of the background construction technique and the theory and approximation leading to the summing corrections.
TABLE 4. Experimentally determined conversion ratios for the calibration standards and their comparison to values from Table 2

<table>
<thead>
<tr>
<th>Parent Nuclei</th>
<th>Conversion Ratio Calculated in Appendix I</th>
<th>Error Relative to Value from Table 2</th>
<th>$\frac{n_k}{n_{LM}}^a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{109}\text{Cd}$</td>
<td>K/LM = 0.80</td>
<td>$-4.8%$</td>
<td>0.73</td>
</tr>
<tr>
<td>$^{114}\text{In}$</td>
<td>K/LM = 1.01</td>
<td>$-1.0%$</td>
<td>0.93</td>
</tr>
<tr>
<td>$^{113}\text{Sn}$</td>
<td>K/LM = 4.20</td>
<td>$0.0%$</td>
<td>3.43</td>
</tr>
<tr>
<td>$^{137}\text{Cs}$</td>
<td>K/LM = 4.46</td>
<td>$-3.0%$</td>
<td>3.91</td>
</tr>
<tr>
<td>$^{203}\text{Hg}$</td>
<td>K/L = 3.48</td>
<td>$+4.5%$</td>
<td>3.49</td>
</tr>
</tbody>
</table>

$L/MN = 3.04$ | $-5.9\%$ | 2.75 |

$^a_{n_k/n_L}$ and $n_L/n_{MN}$ for $^{203}\text{Hg}$.
CHAPTER V

MEASUREMENT OF CONVERSION COEFFICIENTS

Assignment of transition multipolarities can be made by comparing experimental and theoretical conversion coefficients just as in the case of conversion ratios. In general, for a given energy, conversion coefficients cover a greater range of values and are more widely separated than conversion ratios; thus a conversion coefficient measurement is more likely to enable a definite assignment than a conversion ratio measurement, assuming equal accuracy. Unfortunately, the conversion coefficient is the more difficult of the two quantities to measure since it involves the intensity ratio of two different types of radiation. Several methods of measuring conversion coefficients have been considered and are discussed below. The methods discussed are not necessarily the easiest or most accurate but are the ones possible with the available equipment. The methods are distinguished by the way in which the gamma rays are detected.

Gamma-ray detection in Ge(Li) or NaI(Tl) detector

The gamma-ray spectrum may be obtained with either a Ge(Li) or NaI(Tl) detector and the relative intensities derived using the efficiency curve for the detector. The relative conversion electron intensities are obtained from the Si(Li) detector. The conversion
coefficients for the transitions observable in both spectra can be computed if the two sets of relative intensities can be quantitatively related to one another. If the conversion coefficient for one of the transitions is known, then that is sufficient.

The relation between gamma-ray and conversion electron relative intensities may also be established by measuring the relative efficiency of the two detectors with a different source having a transition with a known conversion coefficient. Note that measuring the relative efficiency of the two detectors at more than one energies amounts to measuring the relative efficiency curve of the gamma-ray detector, since the efficiency of the Si(Li) detector is independent of energy. This redundant measurement of the gamma-ray detector efficiency would be one way to obtain an estimate of the accuracy of this technique.

**External conversion of gamma rays**

The external conversion technique has long been used in conjunction with beta-ray magnetic spectrometers. The procedure when using a Si(Li) detector is as follows. First, the gross conversion electron spectrum is measured in the usual way. Second, a Be absorber and a thin, high Z converter are placed between source and detector with the converter next to the detector. In this configuration the spectrum of externally converted electrons plus the gamma-ray spectrum is recorded. Finally, the converter is removed and the spectrum of gamma rays alone is measured. Note that the converter must be thin enough to allow photoelectrons to pass through it with little energy loss; thus it has very small
attenuation for the gamma rays. The net spectra of internal conversion electrons and the net spectra of external conversion electrons are obtained by subtracting the gamma-ray spectra from the spectra measured in the first two steps above.

The approximate K-conversion coefficient is given by the equation

$$\alpha_K = \frac{n_K}{n_P} \frac{f_p t}{S},$$

(9)

where $n_K$ is the net counts per unit time in the K-conversion electron peak, $n_P$ the net counts per unit time in the externally converted electron peaks (photo electrons from the K-shell, L-shell, etc.), $f_p$ the fraction of incident gamma rays absorbed in the converter in photoelectric events, $t$ the gamma-ray transmission of the Be absorber, and $S$ the appropriate correction for summing of K-conversion electrons with coincident x rays or other radiation. For the calibration standards other than $^{203}$Hg the summing correction is

$$S = 1 - \Omega \left[ \omega_K f_K + \omega_L MN (1 - \omega_K) \right]$$

where all the quantities are as defined in Chapter IV. The correction for $^{203}$Hg is somewhat more complex but follows from the arguments in Chapter IV. If the total conversion coefficient is desired, then $n_K$ is replaced by $n_K + n_{L,M,N}$ and $S = 1$ in Equation (9).

Equation (9) is only an approximation to the conversion coefficient. The reason for this is that it does not take into account the angular distribution of the photoelectrons from the
As the gamma-ray energy decreases, the photoelectrons are ejected at an increasingly greater average angle to the forward direction. This results in greater loss of electrons in the converter through scattering. If there were no other sources of error, the conversion coefficient given by Equation (9) would be too large at low energies and would approach the correct value as energy increases. However, by performing measurements on the calibration standards, it might be possible to establish an energy dependent calibration for this technique. Whether or not this approach holds promise can be seen by comparing the conversion coefficients from Equation (9) with those from Table 2. If the plot of error vs energy allows a smooth curve to be drawn through the points, then the resulting curve could be used as a calibration for the external conversion technique.

Conversion coefficients were measured for all the calibration standards except $^{114}$In. A 9.37 mg cm$^{-2}$ Au converter was used for $^{137}$Cs, $^{113}$Sn, and $^{203}$Hg and a 3 mg cm$^{-2}$ Pd converter for $^{109}$Cd. The detector was at room temperature. For the first three standards the externally converted electron spectrum has a strong peak corresponding to conversion in the K-shell and weaker peaks from conversion in the L-subshells. Also, there is a tail on the low energy side of the K-peak that introduces some uncertainty in the total count rate. For $^{109}$Cd no peak whatever was present, and a coefficient could not be calculated.

The conversion coefficient calculated using Equation (9) and the percentage error relative to the values from Table 2,
column 9, are given in Table 5. The percentage error does show roughly the expected energy dependence, but the points do not fall on a smooth curve. It is not clear either why the values for $^{137}\text{Cs}$ and $^{113}\text{Sn}$ are low. Because of these poor results, this technique has not been pursued further. However, for energies above several hundred kiloelectron volts it may still hold promise.

**TABLE 5.** Comparison of conversion coefficients computed from Equation (9) with those from Table 2

<table>
<thead>
<tr>
<th>Parent Nuclei</th>
<th>Computed from Equation (9)</th>
<th>Error Relative to Value from Table 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{137}\text{Cs}$</td>
<td>$\alpha_k = 0.083$</td>
<td>$-12%$</td>
</tr>
<tr>
<td>$^{113}\text{Sn}$</td>
<td>$\alpha = 0.50$</td>
<td>$-11%$</td>
</tr>
<tr>
<td>$^{203}\text{Hg}$</td>
<td>$\alpha_k = 0.22$</td>
<td>$+35%$</td>
</tr>
<tr>
<td>$^{105}\text{Cd}$</td>
<td>$\alpha$</td>
<td>-</td>
</tr>
</tbody>
</table>

*a*Externally converted electrons not sufficiently intense for quantitative analysis.

**Gamma-ray detection in Si(Li) detector**

This technique was originally thought to hold the least promise, but this did not prove to be true. The conversion electron and gamma-ray spectrum are separately measured as before using the Si(Li) detector. The gamma-ray spectrum alone is measured by absorbing the electrons with a Be absorber. The conversion coefficient is

$$\alpha_k = a \frac{\hat{n}_K}{\hat{n}_\gamma} \frac{f_{\gamma,t}}{dS}$$

(10)
where \( \dot{n}_K \) and \( \dot{n}_\gamma \) are the net count rates in the K-conversion electron peak and gamma-ray peaks respectively, \( f_\gamma \) the fraction of gamma rays absorbed in the detector in photoelectric events, \( t \) the transmission of the Be absorber, \( S \) a correction to account for summing of K-conversion electrons and x rays, and \( d \) the peak-to-total ratio for electrons. The coefficient, \( a \), is an energy dependent calibration factor to be determined by measurement of the conversion coefficients of the calibration standards. The test of the success of this technique is whether or not the values of the calibration factor, \( a \), for these standards allow a smooth, reasonable, calibration curve to be drawn.

The general behavior of the calibration factor, \( a \), as a function of energy is difficult to predict. In Equation (10) the efficiency of the detector for gamma rays is, to first order, \( f_\gamma \), where

\[
 f_\gamma = 1 - e^{-1.06 \mu_\gamma \rho x}
\]

This is exactly the same as Equation (5). (The 1.06 coefficient assumes the measurements will be made at a source-detector spacing of 1 cm.) But as energy increases, multiple events (Compton scattering followed by photoelectric absorption) contribute an increasing fraction of the counts under the full energy absorption peak. Thus the true efficiency is greater than \( f_\gamma \), tending to make \( a > 1 \) and to increase with energy. Conversely, as energy increases an increasing fraction of the photoelectrons will escape through the rear surface of the detector. Except for very low energies the number of photoelectrons produced per unit thickness
is the same at all depths in the detector, but their range increases with increasing energy. This tends to make \( a < 1 \) and to decrease with energy. Which of these two opposing effects predominates is not obvious. However, it does seem clear that there should be no rapid variation in the calibration factor, \( a \), as energy varies. It also appears that as the energy decreases, the calibration factor, \( a \), should approach a value near one. The exact value would be determined by other factors not accounted for in Equation (10). One such factor is L-shell external conversion in the gold window. An estimate indicates that only a few percent of the counts in the gamma-ray peak are from this source so an explicit term to account for this has not been included in Equation (10).

Values of the calibration factor, \( a \), for all five calibration standards are shown in Figure 7. Appendix II contains work sheets for each calibration standard showing both the conversion electron and gamma-ray spectra and giving values for all parameters required in the calculation of the calibration factor, \( a \). In Figure 7 the circles designate values from Appendix II and are derived from data obtained with the present detector. The triangles designate values derived from data obtained with the previous detector. In all cases the detector was operated at room temperature. The close agreement between the two sets of values supports the belief that the detectors are substantially identical. Assuming they are identical then the close agreement illustrates the reproducibility of the measurement of the calibration factor, \( a \). (Taken alone this would be a circular argument;
Fig. 7. Calibration factor, α, in Equation (10) vs energy. Error bars are for circled points.
however, there is no reason to suspect the detectors were not identical.) Possible errors have been estimated, and are shown, for the values obtained with the present detector. Errors for the values measured with the previous detector are the same for each energy. In drawing the calibration curve slightly greater weight was given to the values for the present detector, and both values for $^{114}$In were ignored.

There are several justifications for ignoring the $^{114}$In data. First, it has the greatest possible error of all the points. Second, the curve is well defined by the other points. It cannot pass through or near the $^{114}$In points without either being in disagreement with the more accurate data or having an unreasonable shape. Third, the value of the calibration factor, $\alpha$, for $^{114}$In is based on $\alpha = 4.8$ which is derived from the theoretical value of $\alpha_k$ (Table 2, column 9). If the calibration curve, as shown, is assumed correct and the $^{114}$In data (present detector) is regarded as an experimental measurement of the total conversion coefficient, then the value derived is $\alpha = 4.3$. The other experimental value reported (5) are 4, 4.6, and 4.3. Thus, the value measured here is in good agreement with other measured values.

This is not to say that the theoretical value is incorrect, only that there seems some room for doubt.

The accuracy of the calibration curve cannot be stated precisely. Certainly the accuracy is better than $\pm 10\%$ over the entire range of energies covered, and it does not seem unreasonable to believe the accuracy to be $\pm 5\%$. Finally, it is noted that if
all the points, including $^{114}$In (present detector), are given equal weight, the best straight line through them is at most 7% different from the curve shown.

The shapes of the gamma ray peaks—measured with the Si(Li) detector—have an energy dependence which is not entirely understood. Figures 19-23 show the gamma-ray spectra for each standard in the region of the peak. The hump on the low energy side of the peak becomes increasingly prominent as energy increases. The resolution also increases as energy increases. A part of this hump is probably due to photoelectrons produced in the gold window of the detector. The energy of photoelectrons from the gold L$_{III}$-subshell is about 12 keV less than the incident gamma-ray energy. The loss of photoelectrons produced in the detector volume may partly account for the hump. In any event, the shape is reproducible; and if the peak count rate is always measured in a uniform way, it should cause no difficulty.

The calibration curve depends on the exact values for the photoelectric absorption coefficient although errors in the absorption coefficient will be accounted for by the calibration factor, $a$. The values for Si used here were obtained from reference 5, Appendix I and are listed in Table 6. The values for 500, 600, and 700 keV are extrapolations from lower energy.
<table>
<thead>
<tr>
<th>Energy (keV)</th>
<th>Photoelectric Absorption Coefficient (cm$^2$ gm$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>30.9</td>
</tr>
<tr>
<td>15</td>
<td>9.3</td>
</tr>
<tr>
<td>20</td>
<td>3.88</td>
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<tr>
<td>30</td>
<td>1.11</td>
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<tr>
<td>40</td>
<td>0.438</td>
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PART II

STUDIES OF A RADIOACTIVE DECAY SCHEME
CHAPTER VI

RADIOACTIVE DECAY OF $^{97}$Ru

Introduction

The discovery and identification of the 2.8-day electron capture activity of $^{97}$Ru was made by Sullivan, Slight and Gladrow (10). Subsequently Cook, Brice, Schmid and Helmer (11) reported transitions of 90, 99, 109, 216, 325, and 570 keV and observed coincidence between the 109- and 216-keV gamma rays. They attributed the 90- and 99-keV transitions to the decay of the 91-day isomer in $^{97}$Tc. This isomer was first reported by Cacciapuoti and Segre (12) and assigned to $^{97}$Tc by Kotta, Boyd and Brosi (13). The isomer was further studied by Unik and Rasmussen (14) who obtained K-, L-, and M-shell conversion electron relative intensities for a 97-keV transition but found no evidence for a 90-keV transition. Their K/L ratio and the half-life of the level are consistent with an M4 transition. The data on the $^{97}$Ru decay through 1959 is summarized in the Nuclear Data Sheets (5), and a decay scheme with levels at 0 $(9/2^+)$, 97 $(1/2^-)$, 216 $(5/2^+, 7/2^+)$, and 325 keV is given. The position of the 570-keV transition in the decay scheme could not be determined from the data.

Preparation of samples

Finely powdered Ru metal enriched to 95% in $^{96}$Ru was irradiated for 3.3 days in a neutron flux of $\approx 2 \times 10^{13}$ cm$^{-2}$ sec$^{-1}$.
in the Battelle Memorial Institute Research Reactor. Two days after the end of the irradiation the majority of the material, \( \approx 1.5 \text{ mg} \), was used to prepare a gamma-ray sample, N2178. A sample for electron counting, N2179, was prepared by spreading some of the powder on a thin aluminized mylar backing and covering with a zapon film of \( \approx 30 \text{ micrograms/cm}^2 \). This sample, N2179, was thick enough to appreciably broaden the lower energy conversion electron peaks but was strong enough to allow the weak, higher energy conversion electrons to be observed with reasonable counting times. A thinner, weaker sample, N2183, was prepared by dissolving a small amount of the irradiated material in aqua regia, drying onto a mylar backing, and covering as above.

**Gamma-ray spectra**

Figure 8 shows the gamma-ray spectrum obtained with a 10 mm diameter, 1-mm thick Ge(Li) detector, and recorded with a 400-channel analyzer. Those peaks with energies indicated are assigned to the decay of \( ^{96}\text{Ru} \). The half-lives of all eleven peaks were measured. The 216-keV peak was followed through nine half-lives and gave a value of \( 2.82 \pm 0.04 \) days. All other peaks assigned to the \( ^{96}\text{Ru} \) decay have measured half-lives in close agreement with this value. The worst deviation is for the weak 642-keV peak which is superimposed on the Compton edge of the 842-keV gamma ray making background subtraction uncertain. Its measured half life is \( 2.6 \pm 0.6 \) days. The peak at 498 keV is assigned to 40-day \( ^{103}\text{Ru} \) and decays with that half-life. The weak 698-keV peak decays with a half-life of \( < 1.8 \) days and has not been identified. The 771-,
Fig. 8. Gamma-ray spectrum of $^{97}$Ru.
806-, and 842-keV peaks have a 4.2-day half-life and are assigned to $^{96}\text{Tc}$. A spectrum covering the energy region up to 1600 keV revealed only the $^{96}\text{Tc} 1119$-keV gamma ray.

The relative intensities of the $^{97}\text{Ru}$ gamma rays are given in column 2 of Table 7. The count rate under each peak has been corrected for the photopeak efficiency of the germanium detector. The possible errors given are estimates which take into account the uncertainty in detector efficiency, counting statistics, and uncertainty in background subtraction. A 177-keV gamma ray is not detectable in Figure 8 but is found in the coincidence spectra discussed below. The upper limit on its relative intensity given in Table 7 is based on the spectrum shown in Figure 8.

**Gamma-ray coincidence spectra**

Gamma-ray coincidence data were taken with $1.75 \times 2$ in. NaI (Tl) crystals at $180^\circ$. A four-gate fast coincidence unit with a resolving time of $2\gamma \approx 30$ nanoseconds and a 400-channel analyzer enabled four coincidence spectra of 100 channels each to be simultaneously recorded. The presence of the 771-, 808-, and 842-keV gamma rays from $^{97}\text{Tc}$ which are in cascade contributes a high coincidence background to the data since Compton events from one can be recorded when a Compton event from another triggers the gate. To allow correction for this one gate was set on the 498-keV $^{103}\text{Ru}$ gamma ray which is not in coincidence with other gamma rays. This location was chosen because 498 keV is on the Compton distribution from the $^{97}\text{Tc}$ gamma rays but of higher energy than most of the spectrum from $^{97}\text{Ru}$. There is unfortunately some overlap
<table>
<thead>
<tr>
<th>Transition Energy keV</th>
<th>Gamma-Ray Relative Intensities</th>
<th>K-conversion Electron Relative Intensities&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Assumed K&lt;sub&gt;K&lt;/sub&gt; (216 keV) = 0.032</th>
<th>Transition Probability&lt;sup&gt;b&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>109 ± 1</td>
<td>0.4 ± 0.1&lt;sup&gt;c&lt;/sup&gt;</td>
<td>2.5 ± 0.6</td>
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<td>0.42 ± 0.10</td>
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<td>177 ± 5</td>
<td>&lt;0.2</td>
<td>&lt;2</td>
<td></td>
<td>&lt;0.22</td>
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<tr>
<td>216 ± 1</td>
<td>100</td>
<td>100</td>
<td></td>
<td>83.8 ± 2.0</td>
</tr>
<tr>
<td>325 ± 1</td>
<td>12.8 ± 0.6</td>
<td>7.9 ± 0.4</td>
<td>0.020</td>
<td>10.8 ± 0.6</td>
</tr>
<tr>
<td>462 ± 2</td>
<td>0.16 ± 0.03</td>
<td>0.031 ± 0.010</td>
<td>0.0062</td>
<td>0.14 ± 0.03</td>
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<tr>
<td>569 ± 2</td>
<td>1.33 ± 0.16</td>
<td>0.106 ± 0.014</td>
<td>0.0026</td>
<td>1.14 ± 0.14</td>
</tr>
<tr>
<td>642 ± 4</td>
<td>0.030 ± 0.015</td>
<td></td>
<td>0.027 ± 0.014</td>
<td></td>
</tr>
<tr>
<td>751 ± 3</td>
<td>0.110 ± 0.025</td>
<td>0.0031 ± 0.0016</td>
<td>0.0009</td>
<td>0.094 ± 0.022</td>
</tr>
</tbody>
</table>

<sup>a</sup>The L + M relative intensities for the 216- and 325-keV transitions are 17.0 ± 1.7 and 1.60 ± 0.16 respectively.

<sup>b</sup>Transitions for 100 decays of ⁹⁷Ru.

<sup>c</sup>Derived from conversion electron intensity assuming M1 transition.
between this gate and the 462-keV gamma ray; however, to go to higher energy produces overlap with the 569-keV gamma ray. Other gates were set on the 216-, 325-, and 569-keV gamma rays. After random subtraction the spectrum with the 498-keV gate was subtracted from the others. Figure 9 shows the normal spectrum and the three coincidence spectra after subtraction of the 498-keV gate spectrum.

With the gate on 216-keV the 109- and 569-keV peaks are prominent. The broad, weak hump in the 177- to 216-keV region is attributed to true coincidence between 216 keV and the Compton distribution of 569 keV, and true coincidence between 177 keV and the Compton distribution of 462 keV. Some of the 177-keV counts in the hump may be from coincidence between 117 and 216 keV; but, if this is the case, the number of 177-216 keV coincidence counts is small compared to the number of 569-216 keV coincidence counts.

With the gate on 325 keV the 177- and 462-keV peaks are prominent. The 216-keV counts are attributed to coincidence between 216 keV and the Compton from 569 keV. The peaks at 569 and 642 keV are barely of statistical significance, especially the 569-keV peak. Both peaks fall in the region of the Compton edges for the 97Tc gamma rays, where the net counts after subtraction of the 498-keV spectrum are about 1/3 the gross counts. Thus, it is difficult to decide on the basis of the 325-keV gate spectrum alone whether or not either or both peaks represent true coincidence with the 325-keV gamma ray. As discussed below, the 569-keV gate spectrum gives no evidence for coincidence between 569 and 325 keV. This, together with the level scheme suggested by the other data,
Fig. 9. Gamma-ray normal and coincidence spectra.
leads to the conclusion that the 569-keV and 325-keV gamma rays are not in coincidence but that the 642-keV and 325-keV gamma rays are.

With the gate on 569 keV, the 216-keV peak is very strong. There is some broadening on the low energy side of the 216-keV peak which could be caused by coincidence between 569 and 177 keV. By subtracting out the 216-keV peak using the peak shape from the normal spectrum, an upper limit of about 20:1 on the ratio of 216- to 177-keV gamma rays in the 569-keV gate spectrum has been obtained. Because of this large difference in strength and the uncertainty of the background of the 216-keV peak, the existence of 177-keV gamma rays in coincidence with 569 keV is questionable. There is no evidence for coincidence between the 569 keV and gamma rays other than 216 keV and possibly 177 keV.

**Conversion electron spectra**

Figure 10 shows the conversion electron spectrum taken with the detector cooled. Transition energies for K-shell conversion peaks from the decay of $^{97}$Ru are indicated. The LM peak and the sum peak of L- or M-conversion electrons and the electron capture K-x ray is apparent in some cases. Other peaks are attributed to $^{103}$Ru and $^{96}$Tc decay. The spectrum below channel 170 is from the weaker source, N2183, and above channel 170 from the stronger, thicker source, N2179. The spectra were normalized using the total counts under the 325-keV peaks. The gamma-ray response of the detector contributes appreciably to the gross counts and in
Fig. 10. Conversion electron and Si(Li) detector gamma-ray spectrum of $^{97}\text{Ru}$.
Figure 10 has been subtracted out. The gamma response alone was obtained by selectively absorbing the electrons with a Be absorber.

Column 3 of Table 7 gives the relative intensities of the observable conversion lines and an upper limit on the relative intensity of the 177-keV transition which is not observable in Figure 10. These data have been corrected for summing between the electrons and the coincident x rays or Auger electrons. The possible error in the conversion electron relative intensities for the 462-, 569-, and 751-keV transitions includes an estimated possible error of 10% in the normalization of the spectra from the two sources although it is probably less than this.

Conversion coefficients were derived in two ways, both using the conversion electron data just discussed. For the 216- and 325-keV transitions the gamma rays were detected with the Si(Li) detector under the same conditions as for the electrons except that a 541 mg cm$^{-2}$ Be absorber allowed only gamma rays to enter the detector. The gamma-ray spectrum thus obtained is shown dashed in Figure 10. Summing the counts under the K-peak and gamma-ray peak in Figure 10, subtracting the indicated background, and dividing by the live time, one obtains for the 216-keV transition $\dot{n}_K = 1255$/min and $\dot{n}_\gamma = 41.9$/min. Also:

\[ \Omega = 0.057 \]
\[ f_\gamma = 0.00103 \]
\[ t = 0.945 \]
\[ d = 0.77 \]
\[ \omega_K = 0.75 \]
\[ f_K = 0.92. \]
Substituting these values in Equation (10) with $S = 1 - \Omega [\omega K f_K + (1 - \omega K) \Delta]$ = 0.95 and the calibration factor, $a = 0.76$, from Figure 7, the K-conversion coefficient for the 216-keV transition is found to be $\alpha_K = 0.0320 \pm 0.0045$. Similarly for the 325-keV transition: $\hat{n}_K = 99.4\, \text{min}, \hat{n}_\gamma = 2.12\, \text{min}, \alpha = 0.71, f_\gamma = 0.000352, t = 0.952$, and the other parameters are the same as for the 216-keV transition. Equation (10) gives for the 325-keV transition, $\alpha_K = 0.0162 \pm 0.03$.

For the higher energy transitions the gamma-ray lines are too weak for the above technique. The conversion coefficients for these transitions are obtained from the relative intensities given in Table 7 using the coefficient for the 216-keV transition given above to relate the gamma-ray and K-conversion electron relative intensities. The results are given in Column 4. Figure 11 compares the experimental conversion coefficients with theoretical values from Rose (7).

From Figure 10 it is seen that conversion ratios may be computed for the 216- and 325-keV transitions. For reasons that will become clear later, the conversion ratios will first be computed using Equation (3) and expression (5) which assume one K-x ray or Auger electron in coincidence with the K-conversion electron. From Figure 10 one finds for the 216-keV transition $n_K = 188,000$ and $n_{LM} = 43,600$, and for the 325-keV transition, $n_K = 14,900$ and $n_{LM} = 4,020$. With $\Omega = 0.057, \alpha = 0.77$, and $f_K = 0.92$, the K/LM ratios for the 216- and 325-keV transitions are $5.9 \pm 0.6$ and $4.9 \pm 0.7$ respectively. In Figure 12 these data
Fig. 11. Comparison of experimental and theoretical K-shell conversion coefficients.
are indicated by the circled points labeled "one coincident x ray," and the solid lines are theoretical curves derived from Rose (7).

Both the 216- and 325-keV transitions follow electron capture, and the coincidence data indicates that both transitions occur promptly (for the amplifier time constants involved here) after the upper levels of the two transitions are populated. There should, therefore, be electron capture K-x rays in coincidence with the conversion electrons in addition to the x rays following internal conversion. If two coincident K-x rays are assumed to be in coincidence with the conversion electrons, the equation for K/LM becomes

\[ \frac{K}{LM} = \frac{n_K}{n_{LM}(1 - \Omega f_L)^2 - n_K(\Omega f_K)(2 - \Omega f_K)} \]

In Equation (11) it is assumed that \( \omega_K = 1 \); to remove this assumption \( f_K \) should be replaced by expression (5) as discussed in Chapter IV. When L-capture occurs, the L-series x ray and Auger electrons do not have sufficient energy to move a count out of the K-peak, and the assumption of only one coincident x ray is correct. Where both K- and L-capture occur, the conversion ratio is the appropriately weighted average of the ratios calculated assuming one and two coincident K-x rays.

From the same experimental data used to calculate the conversion ratios assuming one coincident x ray, the conversion ratios have been calculated assuming two coincident x rays. The results have been averaged with the previous results for one coincident x ray assuming an L- to K- capture ratio of 0.10 as given by
Wapstra (8). The average K/\textit{LM} ratios obtained are 9.3 ± 0.9 and 6.8 ± 1.0 for the 216- and 325-keV transitions respectively, and are designated by the triangles in Figure 12. These points are labeled "two coincident \textit{x} rays" since K-capture is the predominant decay mode.

In the next section the 216- and 325-keV transitions will be assigned multipolarities of M1 and E2 respectively. It is seen from Figure 12 that the conversion ratios calculated assuming one coincident \textit{x} ray are in agreement with this assignment. When two coincident \textit{x} rays are assumed, the conversion ratios do not agree with the assignment. More significantly, the 216-keV ratio for two coincident \textit{x} rays is far above the theoretical value for any multipolarity. This result is surprising since two coincident \textit{x} rays would be thought to be the correct assumption. In view of the results obtained in Chapter IV it is difficult to see how the K/\textit{LM} calculation itself could be sufficiently in error to account for the discrepancy. A possible explanation of the discrepancy would be to have an angular correlation between the conversion electron and one of the two K-\textit{x} rays. The correlation would have to be such that the \textit{x} ray and electron have a low probability of being emitted within roughly 45° of one another. Both \textit{x} rays would still be in coincidence with the K-conversion electron, but as far as the summing correction is concerned there would be only one coincident \textit{x} ray. Note that no type of correlation between the two \textit{x} rays would remove the discrepancy.
Fig. 12. Comparison of experimental and theoretical conversion ratios.
It is not proposed that such an angular correlation exists. It is only pointed out that this is a way in which the discrepancy can be explained. No theoretical consideration of such a correlation has been found, and no attempt has been made to ascertain if such a correlation is reasonable from a theoretical point of view.

In calculating the conversion coefficients a summing correction, $S = 0.95$, was used. This summing correction was based on the assumption of one coincident x ray. The conversion ratio calculation would indicate this to be the correct assumption; however, there is some question. Fortunately the conversion coefficients are not very sensitive to the choice of one or two coincident x rays. For two coincident x rays the correction term, $S$, would change from 0.95 to 0.90. This would increase all the conversion ratios by about 5% and as seen from Figure 11 would not change any conclusions regarding multipolarity assignment.

Discussion of results

The proposed decay scheme is shown in Figure 13. The ground level spins and parity for parent and daughter are taken from reference 5 and are based on shell model predictions and analogy to similar nuclei. The 97-keV ($1/2^-$) isomeric level is based on the work discussed in the Introduction to this chapter. From the proposed decay scheme and the data on gamma-ray and conversion electron intensities, the transition probabilities have been calculated and are given in the last column of Table 7. The gamma-ray intensity of the 109-keV transition has been derived from
Fig. 13. Proposed decay scheme of $^{97}$Ru.
the conversion electron intensity assuming an M1 transition. The resulting 109-keV gamma-ray intensity is well below that which would give an observable gamma ray in Figure 8.

The two levels at about 785 keV, designated 785 keV (A) and 785 keV (B) are separated by no more than 6 keV based on the possible errors in the transition energies given in Table 7. Which of the two levels at about 785 keV has the higher energy is unknown; the order shown in Figure 13 is only for illustration. From the transition energies alone, the decay scheme would be as shown in Figure 13 except that only a single level would be proposed at 785 keV. Two closely spaced levels are proposed to account for the gamma-gamma coincidence data. Gating on 325 keV, it is found that for every 462-keV gamma ray in coincidence with 325 keV there is approximately one 177-keV gamma ray in coincidence with 325 keV. Gating on 569 keV, few, if any, 177-keV gamma rays are observed. These coincidence data cannot be satisfied by a single level at 785 keV populated mainly by electron capture and slightly by the 177-keV transition. In this case the relative gamma ray intensities observed in the 325-keV gate coincidence spectrum and the relative transition probabilities in Table 7 cannot be simultaneously achieved. On the other hand, the absence of a strong coincidence between 177 and 569 keV and the upper limit on the 177-keV transition probability given in Table 7 rule out a single level at 785 keV populated by the 177-keV transition. According to the proposed decay scheme the 177- and 462-keV transition probabilities are the same: 0.14. This value is consistent with the
upper limit of 0.22 for the 177-keV transition probability given in Table 7.

From Figure 11 the 216- and 325-keV transitions are clearly M1 and E2 respectively. This permits a spin and parity assignment of $\frac{7}{2}^+$ to the 216-keV level and $\frac{5}{2}^+$ to the 325-keV level. The conversion coefficients for the 462- and 569-keV transitions permit either to be M1 or E2. For the 785-keV (A) level, the possible spins include all values between $\frac{1}{2}$ and $\frac{9}{2}$, and the level has even parity. Since electron capture from the $\frac{5}{2}^+$ ground level of $^{97}$Ru to the 785-keV (A) level is negligible, spins of $\frac{3}{2}$, $\frac{5}{2}$, and $\frac{7}{2}$ are ruled out. The two remaining choices are $\frac{1}{2}$ and $\frac{9}{2}$. The 785-keV (A) level is shown decaying to the $\frac{5}{2}^+$, 325-keV level but not to the $\frac{7}{2}^+$, 216-keV level, and, therefore, a spin of $\frac{1}{2}^+$ is tentatively assigned to the 785-keV (A) level.

A tentative assignment has not been made for the 785-keV (B) level. The 569-keV transition is either M1 or E2 which would indicate even parity and allow any spin from $\frac{3}{2}$ to $\frac{11}{2}$. In order to have electron capture to the 785-keV (B) level, the choice is restricted to $\frac{3}{2}^+$, $\frac{5}{2}^+$, or $\frac{7}{2}^+$, but further selection would be highly uncertain with the available data. From Figure 11 the multipolarity of the 751-keV transition is indicated to be M1, E1, or E2. Similar agreements to those just given suggest that the spin and parity of the 967-keV level is $\frac{3}{2}^+$, $\frac{5}{2}^+$, or $\frac{7}{2}^+$, but selection among these possibilities is not possible from the data.
As a check on the proposed decay scheme the intensities of the K-x rays and the 216-keV gamma rays were compared. A 3 x 3 in. NaI (Tl) detector was used. According to the proposed decay scheme the ratio of K-x rays to 216-keV gamma rays is 0.80 assuming the L- to K-capture ratio is 0.10 and the fluorescent yield is 0.75. The experimentally determined ratio is 0.75 ± 0.10. This is in satisfactory agreement with the proposed decay scheme.

After substantially complete decay of the \(^{97}\text{Ru}\), electrons from the 97-keV isomeric transition in \(^{97}\text{Te}\) were observed. Through a comparison of the intensity of these electrons with the intensity of the 216-keV transition shortly after the irradiation, the total transition probability to the 97-keV level was found to be 0.03 ± 0.01. The K/\text{LM} ratio for the 97-keV transition was also measured and found to be 1.6 ± 0.4. This is in agreement with the value 1.6 found in reference 14 and supports the M4 multipolarity assignment to the isomeric transition.
SUMMARY

A conversion electron spectrometer employing a lithium drifted silicon detector has been constructed, and its operating characteristics determined. Techniques for the measurement of conversion ratios and conversion coefficients have been developed and tested with well understood calibration sources.

The most significant results obtained in this study are new data on the decay of $^{97}$Ru. Previous work had identified several transitions and enabled construction of a partial decay scheme with spin and parity assigned to the isomeric level. In this study several additional transitions have been identified through the use of solid state detectors for both gamma rays and conversion electrons, and additional energy levels are proposed to account for them. Gamma-gamma coincidence results confirm the levels proposed on the basis of transition energies alone and give additional information on the decay scheme. Conversion coefficients measured for five of the transitions allow spin and parity to be assigned to two excited levels and limit the possible assignments for three other levels. From the gamma ray and conversion electron relative intensities and the measured conversion coefficients, transition probabilities are derived for the decay of $^{97}$Ru.
APPENDIX I

WORK SHEETS FOR CONVERSION RATIO CALCULATION

Figures 14-18 show work sheets for the calculation of the conversion ratios of the calibration standards. The conversion electron spectra and the background, constructed according to the discussion in Chapter IV, are shown, together with all parameters required in the conversion ratio calculation. In computing \( \frac{K}{LM} \) for the calibration standards other than \( ^{203}\text{Hg} \), Equation (3) with expression (5) substituted for \( f^K \) in Equation (3) is used. For \( ^{203}\text{Hg} \) Equations (6), (7), and (8) are used to find \( N_K \), \( N_L \), and \( N_{MN} \) respectively, from which \( K/L \) and \( L/MN \) are derived.
Fig. 14. Work sheet for $^{109}$Cd conversion ratio calculation.
Fig. 15. Work sheet for $^{114}\text{In}$ conversion ratio calculation.
Fig. 16. Work sheet for $^{203}$Hg conversion ratio calculation.
Fig. 17. Work sheet for $^{113m}$Sn conversion ratio calculation.
Fig. 18. Work sheet for $^{137}$Cs conversion ratio calculation.
Figures 19-25 show work sheets for the calculation of the conversion coefficient calibration factor, $a$, for each calibration standard. The conversion electron spectrum and the background, constructed according to the discussion in Chapter IV, is shown on the left half of each figure. The insert in the upper right of each figure shows the gamma-ray spectrum and the assumed background. The values of all parameters used in Equation (10) for the calculation of the calibration factor, $a$, are given.
Fig. 19. Work sheet for $^{109}$Cd calibration factor.
Fig. 20. Work sheet for $^{114}$In calibration factor.
Fig. 21. Work sheet for $^{203}\text{Hg}$ calibration factor.
Fig. 22. Work sheet for $^{113}$Sn calibration factor.
Fig. 23. Work sheet for $^{137}$Cs calibration factor.
REFERENCES


