MASTER

THE BETA DECAY OF GASEOUS FISSION PRODUCTS

Ph.D. Thesis Submitted to Iowa State University,
February, 1973

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The beta decay of gaseous fission products

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James Kent Halbig

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The beta decay of gaseous fission products

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The development of a Bartlett-type $\pi\sqrt{2}$ double-focusing beta-ray spectrometer for operation on-line to the TRISTAN isotope separator at Ames Laboratory is described. Improvements in the magnetic field control system previously used in this spectrometer are reported. The improvements include the implementation of a six-band programmable digital field selector and a new field stabilization system which has settling times much smaller than those of the original system. The adaptation of a third generation moving tape collector for use in the spectrometer is discussed. Interesting features include use of a special "split" aluminized Mylar tape for ion-beam stabilization inside the spectrome-

ter, tape supply reels which hold approximately five times as much tape as reels used in previous designs, and a tape transport system which allows rapid movement of tape. The investigations carried out with the spectrometer are, briefly, as follows: The beta spectra of ^{85}mKr , ^{87}Kr , ^{88}Rb , and ^{91}Sr were studied to determine the beta end-point energies and the branchings to the ground state. Internal conversion electron intensities were measured for transitions in the decays of ^{85}mKr , ^{88}Kr , ^{90}Kr , ^{91}Kr , ^{91}Rb , ^{91}Sr , and ^{92}Kr .

I. INTRODUCTION

The key to the puzzle of the nuclear interaction force is one of the most sought after goals of physics. One of the more visible results of this interaction is the pattern of excited levels in nuclei, broadly referred to as the nuclear structure. Several models have been developed to explain the nuclear structures observed in various regions of the chart of nuclides; however, even though the models are reasonably accurate in some isolated cases, no model has been proposed which is applicable to all nuclei. The nuclear theorists who develop these models are dependent on experimental physicists to provide data from which new models can be formed and which can be used to check the validity of present models.

The TRISTAN isotope separator group at Iowa State University can study the nuclear structures of short-lived gaseous fission decay products and their daughters. In particular, the Kr isotopes in the mass range $85 \leq A \leq 94$ and the Xe isotopes in the mass range $137 \leq A \leq 144$ are available for study. Recent gamma-ray studies (1)-(5) have resulted in several proposed energy-level diagrams for isotopes in these regions.

The high-resolution gamma-ray work typically places about 98% of the observed gamma-ray intensity into a decay

scheme. The accuracy of the energy measurement varies from 0.1 to 1.0 keV, depending on the intensity of the gamma ray. The relative intensities are less well known due to the non-linear energy dependence of the efficiency of the detector and the uncertainties of the intensities of the gamma rays used in determining the detector efficiency. The knowledge of the relative intensities allows speculations to be made on the multipole order of the transitions which in turn allow one to make spin and parity assignments to levels which are connected to levels of known spin and parity. The calculations of relative intensities also allow one to determine the relative beta feeding to a particular level; for example, a level which is fed by a total relative intensity of 80 and is depopulated by a total relative intensity of 100 must be beta fed by a relative intensity of 20. The relative beta-feeding calculations must also include the internal-conversion contributions to the transition intensities. In the example above, if a single gamma ray populates the level and the gamma transition is converted with an internal conversion coefficient of 0.05, the actual relative feeding would be 84 instead of 80; and the relative beta branching would then be 16 instead of 20.

One can go a step further if the beta branching to the ground state is known. This knowledge allows one to calculate the log ft values of the branches. The log ft values

give an indication of the spin and parity change between the levels involved in the beta decay. If the decay originates from, or goes to a level of known spin and parity, e.g., the ground state of an even-even nucleus, the spin and parity of the unknown state may be deduced, often within small limits. For a specific example consider the decay of ^{88}Rb to the ^{88}Sr ground state, which has spin-parity of 0^+ since ^{88}Sr is an even-even nucleus. The $\log ft$ value of the beta decay of the ground state of ^{88}Rb to the ground state of ^{88}Sr is 9.2, from the work of Bunting (5). Such a $\log ft$ value indicates that the beta decay is of first-forbidden unique character which imposes a spin change of 2 and a parity change. This would indicate then that the ground state of ^{88}Rb has spin-parity of 2^- .

It could be pointed out that the $\log ft$ value of 9.2 is near the lower limit of the range dominated by first-forbidden unique transitions. The alternative choices, of less likely occurrence, would be a first-forbidden non-unique transition or an allowed transition. In such ambiguous cases it is imperative to know the shape of the beta decay spectrum, which is distinctive for a first-forbidden unique transition. Through the use of a high-resolution magnetic beta-ray spectrometer, one is often able to provide the required undistorted data which can reveal the shape of the decay.

The high-resolution magnetic beta-ray spectrometer is a single-channel instrument which selects electrons of a given momentum by selection of the magnetic field through which electrons travel from source to detector. It can be used to measure both internal conversion electron and continuous beta spectra. It has several advantages over other types of beta detectors. It is absolutely calibrated, i.e., the momentum of a detected particle is directly proportional to the field in the spectrometer. Methods now exist (6) which allow linear control of the field to within 1 part in 10^5 , to allow absolute calibration of the instrument using only a single calibration source. Depending upon the type of detector used in the beta-ray spectrometer, the intensity calibration of the instrument above a certain threshold may be absolute as a function of momentum. For a thin-window gas-flow proportional (or Geiger) counter, all electrons having sufficient momentum (energy) to penetrate the window will be counted. The actual threshold of the spectrometer is dependent on the detector window in use. Other types of detectors could also be used, e.g., Si(Li) and plastic scintillator devices; however, these detectors present problems when used in the magnetic spectrometer. The photomultiplier tube cannot be mounted inside the spectrometer since it is sensitive to magnetic fields. Thus the light signal must be brought out of the spectrometer by

means of a light pipe. This greatly degrades the signal-to-noise ratio of such a detector system. The use of the Si(Li) detector suffers from a much greater sensitivity to gamma background than the gas-flow proportional counter.

Finally, the spectrometer is free from spectral distortions which affect plastic scintillator and Si(Li) detectors. Plastic scintillators suffer from inherently poor resolution which requires the response of the detector to monoenergetic electrons to be determined and folded into the analysis of the spectra. Further distortion due to electrons scattering out of the crystal enhances the low-energy portion of the spectrum. A comprehensive treatment of the correction which must be made in order to analyze the spectra is given in reference (7). Although the resolution may be comparable to that of the magnetic spectrometer, Si(Li) detectors have a response which distorts continuous beta spectra. Correction for this distortion must be treated in the same manner as for plastic scintillators. The sensitivity of this type of detector to gamma radiation has been mentioned above as being a disadvantage.

The high-resolution magnetic spectrometer can be used to measure internal conversion electron peaks in the decay spectrum. The use of high resolution, of the order of 0.2%, makes it possible to resolve the K and L+M conversion peaks at around 300 keV and for lower energy transitions, the K, L

and M peaks can be resolved.

The internal conversion electron intensity measurements are a further aid in the determination of the multipolarity of a transition. If the spin and parity of one of the levels is known, then limits can be placed on the values which may be assigned to the spin and parity of the other level associated with the transition. For example, from internal conversion coefficients associated with the 151-keV transition in ^{85}Rb , this transition has a deduced character of M1, as described later. Thus, the transition connects states whose spins differ at most by 1 unit of angular momentum and whose parities are the same. The ground state of ^{85}Rb is $5/2^-$; thus the 151-keV level is either $3/2^-$, $5/2^-$, or $7/2^-$. The beta-transition to the 151-keV level has a log ft value of 5.15 and was found not to have a unique shape. Thus, the transition is an allowed transition implying no parity change and a change in spin of 0 or 1. The level from which the decay originated is $1/2^-$; therefore, only the $3/2^-$ choice is possible for the 151-level in ^{85}Rb .

The Bartlett-type $\pi\sqrt{2}$ magnetic spectrometer which serves as the basis for the work in this thesis is a simple, straight-forward device. Although the implementation for its application in the on-line study of the beta decay of gaseous fission products is perhaps straight forward, it is absolutely not simple! The on-line operation of the spec-

trometer requires position stabilization of the ion beam inside the spectrometer in addition to the beam position stabilization normally used in the isotope separator. Furthermore, the ion beam must be sharply focused on the target inside the spectrometer since a wide source degrades resolution. Beam defining apertures cannot be used to provide narrow sources because activity (which is at a premium since this is a single-channel, low efficiency device) would be lost to the aperture. In addition, any activity deposited on the aperture would act as a secondary source in the spectrometer. Because of the short half-lives of the nuclei studied, a means of isobaric separation (faster than chemical separation) must be provided. Such separation is provided by a moving tape collector system. Use of this single-channel device also requires that the data from all the individual sources be normalized. In multichannel analysis, normalization is not necessary because the total spectrum is being studied simultaneously. The operation of the moving tape collector system must be synchronized with control systems of the magnetic spectrometer which control data collection and the field inside the spectrometer in addition to the control systems of the isotope separator which control beam deposition.

This work describes how these obstacles were overcome, resulting in a unique facility, and also presents the exper-

imental measurements which were made with the system during and after its development.

II. INSTRUMENTATION

A. TRISTAN Isotope Separator Facility

The TRISTAN Isotope Separator Facility (TISF) will be described only briefly since an excellent and complete description of the TISF is given by Olson (8). The layout of the TISF is shown in figure 1. Air brush drawings of parts of the system are shown in figures 2-4. Neutrons from the core of the Ames Laboratory Research Reactor pass through a beam tube and strike an external sample of uranyl stearate. The gaseous fission products are then pumped through the fission product transport line into the ion source. The fission product atoms are ionized, accelerated, focused, and directed into the 1.6-meter 90°-sector-type separator magnet. The mass-separated beam emerges from the separator magnet into the collector box in which the focal plane of the separator is located. The dispersion of adjacent masses in the collector box at mass 88 is approximately 2 cm. All masses except the mass to be studied in a particular experiment are stopped in the collector box. The isobaric beam which exits the collector box travels between two deflection plates and into the switch magnet. The deflection plates are used to control beam deposition at downstream sites by application of a potential between the plates to deflect the beam into the side of the vacuum chamber. At the entrance

Figure 1. Physical layout of the TRISTAN isotope separator facility

Figure 2. Target, source and high voltage section of the TRISTAN isotope separator facility

Figure 3. Separator magnet and collector box of the TRISTAN isotope separator facility

Figure 4. Switch magnet, gamma-ray moving tape collector and beta-ray spectrometer of the TRISTAN isotope separator facility

to the switch magnet is a compression lens which allows control of the height of the beam leaving any of the experimental ports of the switch magnet.

The experimental use of the tape collector available for gamma-ray studies is covered in detail by Olson. The moving tape collector and detector intended for neutron studies are still in the developmental stage. The development and experimental use of the beta-ray spectrometer and its moving tape collector form the subject of this thesis.

B. Beta Spectrometer

1. Spectrometer design

The spectrometer is a $\pi\sqrt{2}$ double-focusing spectrometer, which is patterned after that built by A. A. Bartlett et al (9). A complete description of this spectrometer is given in reference (10). The pertinent details will be summarized here.

The $\pi\sqrt{2}$ double-focusing spectrometer is capable of higher resolution than many other types of spectrometers, a characteristic which is highly useful for the study of short-lived activities. The particular spectrometer described here is also capable of measuring beta-rays with energies in excess of 8 MeV.

The "inside-out" design of Bartlett places the field coils and the "iron core" outside the region which is

Figure 5. Cross-section of the TRISTAN beta-ray spectrometer

tranversed by the electrons (figure 5). This design has several advantages for use with the TISF. The most important is the magnetic shielding provided by the "iron core". Without this shielding the fringe fields of the switch magnet and separator magnet would greatly affect the magnetic field seen by the beta rays under study. Tests carried out by Eitter have shown that the application of the maximum field inside the switch magnet changes the field inside the spectrometer by 60 mG. This change is approximately 0.06% of the field necessary to focus the 661-keV K-conversion line in the decay of ^{137}Cs , or approximately .007% of the maximum field capability of the spectrometer. A second advantage is the radiation shielding provided by the "external core".

A simplified top view of the spectrometer is shown in figure 6. This figure shows the source position, the solid-angle limiting slits, the gas-flow proportional counters, the lead shielding, the NaI(Tl) crystal activity monitor, and the reference solenoid.

The solid-angle limiting slits allow one to define the region of the magnetic field in which the electrons will travel. In this manner, one can reduce the effect of field aberrations and thereby increase the resolving power of the spectrometer at the expense of beta-ray transmission. The setting of these slits is dependent on the type of investi-

Figure 6. Simplified top view of TRISTAN beta-ray spectrometer

gation being made and on the strength of the source being studied, e.g., conversion line studies require good resolution. However, if the source is weak, the transmission must be increased at the expense of resolving power. The gas-flow proportional counters are described elsewhere in this thesis. The lead shielding wedges provide shielding of the gas-flow proportional counter from the gamma rays emitted by the source. The gamma rays would otherwise interact with the detector and give rise to electrons which are counted as background. The NaI(Tl) crystal is used to monitor the source activity as described later in this thesis. Finally, the reference solenoid is used as an element in the field control system.

2. Field control system

The Programmable Digital Field Selector (PDFS) controls the magnetic field in the spectrometer with a hard-wired program which can be preset by the experimenter. It is interfaced with a field stabilization control system and a data acquisition system; both are described below.

The PDFS divides the maximum magnetic field into 500,000 units, or channels. The field calibration is dependent on the field stabilization control system. The PDFS can treat up to six individual regions in this field of 500,000 channels. These regions are called bands and are

determined by a lower limit channel number (LL) and an upper limit channel number (UL). Each band can be made active or inactive with the flip of a switch. An inactive band is skipped when encountered by the PDFS program. The LL of each active band must be greater than or equal to the UL of the preceding active band. The sequence of steps followed by PDFS is given below:

1. The channel number is incremented to the preselected LL of the first active band.
2. The PDFS pauses at this level to allow data to be taken for a preselected length of time or until a continue command is received from an external source. Next it transfers control to a readout interface. (The readout interface is described under the data collection system.) When the readout interface signals that its task is complete the program proceeds.
3. The channel number is increased by a preselected increment Δch .
4. Steps 2 and 3 are repeated until the increment Δch results in a channel number above the preset UL of the band.
5. When the UL in a band is exceeded, the first four steps (which constitute operation within a band) are repeated in the next active band.

6. When operation within the last active band is completed, the channel number returns either to zero or to the LL of the first active band.

There exists a priority interrupt which, if the program is pausing to collect data, will cause this collection to halt; on clearing the interrupt, the data collection is begun over. If the program is in any other step, that step will be completed and the program will halt until the interrupt is cleared.

Operation within a band can be more fully described with the aid of figure 7. The control switches for operation within a band are shown in figure 7a. The upper and lower limits, Δch , and the accumulation time are presettable using three digit thumbwheel switches. The time setting represents the period in tenths of minutes for which the PDFS will pause to allow data to be taken. The possible positions of the digits of these thumbwheel switches relative to the digits of the total channel number is shown in figure 7b. One can select the relative positioning using a multiplier switch. The latter three subfigures correspond to X1, X.1, X.01 positions of this switch. The time setting is not affected by the multiplier switch. Additionally, there is a switch on each band which allows the band to be active or inactive.

UPPER LIMIT

Δ Ch

LOWER LIMIT

TIME

(A)

	XI	X.I	X.OI
UPPER LIMIT	<input type="text"/> <input type="text"/> <input type="text"/> <input type="text"/> <input type="text"/> <input type="text"/>	<input type="text"/> <input type="text"/> <input type="text"/> <input type="text"/> <input type="text"/> <input type="text"/>	<input type="text"/> <input type="text"/> <input type="text"/> <input type="text"/> <input type="text"/> <input type="text"/>
Δ Ch	<input type="text"/> <input type="text"/> <input type="text"/> <input type="text"/> <input type="text"/> <input type="text"/>	<input type="text"/> <input type="text"/> <input type="text"/> <input type="text"/> <input type="text"/> <input type="text"/>	<input type="text"/> <input type="text"/> <input type="text"/> <input type="text"/> <input type="text"/> <input type="text"/>
LOWER LIMIT	<input type="text"/> <input type="text"/> <input type="text"/> <input type="text"/> <input type="text"/> <input type="text"/>	<input type="text"/> <input type="text"/> <input type="text"/> <input type="text"/> <input type="text"/> <input type="text"/>	<input type="text"/> <input type="text"/> <input type="text"/> <input type="text"/> <input type="text"/> <input type="text"/>
CHANNEL NO.	<input type="text"/> <input type="text"/> <input type="text"/> <input type="text"/> <input type="text"/> <input type="text"/>	<input type="text"/> <input type="text"/> <input type="text"/> <input type="text"/> <input type="text"/> <input type="text"/>	<input type="text"/> <input type="text"/> <input type="text"/> <input type="text"/> <input type="text"/> <input type="text"/>
MULTIPLIER SWITCH	XI	X.I	X.OI

(B)

Figure 7. Operation of the control switches of the PDFS
 (a) control switches for operation within a band as they appear on the PDFS, (b) effect of the multiplier switch

The following example will add clarity to the description. A hypothetical conversion electron peak is shown in figure 8a. Let α_1 , α_2 , α_3 and α_4 represent channel numbers 10,000, 11,500, 12,500, and 14,000 respectively, in figure 8a. In regions A and C the Δch increment can be large, say, 25 channels, since the data represent a close approximation to a straight line. In region B the Δch is smaller, perhaps 5 to 10 channels, in order to represent the shape of the peak accurately.

Figure 8b shows a possible program for the PDFS for the example above. The program will begin in the first active band by initially running up to the LL of this band. In this example it will go to channel number 10,000, the LL of band one because the multiplier switch of band 1 is in the X.1 position. It will immediately allow data to be taken at this point for 1.0 minute. The next step is to increment the channel number by 25 to 10,025 and take data for 1.0 minute. This Δch -accumulate cycle continues until the channel number has been incremented to 11,500. Data are accumulated at this point and then, when the time comes to increment the current again, control is passed to band 2 because any increase in the channel number will cause it to exceed the UL of band 1. Note that data will again be taken at channel number 11,500. The Δch -accumulate cycle will be repeated in this band, with a data accumulation time of 0.5 minutes, until channel number

(b)

BAND NO.	1	2	3	4	5	6
UPPER LIMIT	115	125	059	140	125	000
Δ Ch	025	007	050	025	035	000
LOWER LIMIT	100	115	054	125	130	000
TIME	010	005	100	010	150	000
MULTIPLIER	X.1	X.1	X.1	X.1	X.1	X.1
ACTIVE SWITCH	ON	ON	OFF	ON	OFF	OFF

Figure 8. Study of a hypothetical conversion electron peak
 (a) the conversion electron peak, (b) the PDFS
 program

12,494 is reached. The next Δ ch will cause the upper limit to be exceeded; hence, control will be transferred to band 4 since band 3 is inactive. The program will then accumulate data at channel 12,500, and repeat the Δ ch-accumulate cycle for band 4. When the upper limit of band 4 is exceeded, the channel number will be returned either to zero or to the LL of the first active band; the choice is made with a front panel switch. Notice that the position of the thumbwheel switches is immaterial for the inactive bands. It is instructive to consider the alternative that the active switch of band 3 was improperly set to on. In the transition from band 2 to band 3 the field would increment to channel number 54,000 and then commence to accumulate data for 10 minutes, and then proceed in the normal manner until channel number 59,000 was exceeded. Next because the UL of band 3 is greater than the LL of band 4 the field would increment to channel number 112,500 because this is the next time that the number 125 occurs in the fifth, fourth, and third significant digits. The field would then be incremented by 25 channel number steps. In a similar manner, if band 3 had been inactive and band 5 active the field would have gone from channel number 14,000 to 113,000 in the transition from band 4 to band 5.

The magnetic field inside the spectrometer is stabilized using a standard null-probe technique. The magnetic field

control system is shown in figure 9. The PDFS controls relays in a Fluke voltage calibrator, which outputs a voltage proportional to the channel number of the PDFS; channel number 500,000 corresponds to 50 volts output from the Fluke voltage calibrator. The output of the voltage calibrator is linear to within 1 part in 10^5 . This voltage goes to a field stabilizer which attenuates the voltage by factors of 2.5 and 10 and routes these latter voltages to the Alpha Scientific power supply and to the Spectromagnetic power supply respectively. A current proportional to the programming voltage applied by the Alpha Fluke voltage calibrator is provided by the Alpha Scientific power supply to the reference solenoid inside the spectrometer. The Spectromagnetic supply provides the current to energize the coils of the beta-ray spectrometer. A magnetometer null-probe senses any non-zero field at the center of the solenoid and feeds back to the field stabilizer a proportional error voltage. The output of the field stabilizer (which is described below) is an integrated null probe error voltage which is applied to the external programming input of the Spectromagnetic supply, in addition to the attenuated programming voltage from the Fluke voltage calibrator, to null the field at the center of the solenoid.

The magnetic field stabilizer design was changed from the original design (10) which, when tested, revealed three highly undesirable characteristics:

Figure 9. Block diagram of magnetic field control system

1. Drifts exceeding 42 channels were observed.
Such drifts can degrade resolution if they are short term or destroy calibration if they are long term.
2. The stabilization time, i.e., the time after completion of current stepping required for the field to restabilize within 4 channel numbers of the desired field, was found to be 4.8 seconds for a 50 channel step, 8.0 seconds for a 100 channel step and 12.4 seconds for a 1000 channel step. It is clear that for short-lived sources much activity will be lost during field stabilization after a field change.
Furthermore, long stabilization times reduce the duty factor for the experiment, i.e., the ratio of time of source and/or data collection to total time.
3. For field increments larger than 7800 channels the field error became so large that the error signal from the magnetometer probe changed polarity, resulting in system instability.
When this condition results, the spectromagnetic power supply runs up to its maximum current. Protection circuits, which stem this instability by shutting down the

power supply when a set current limit is reached, must be reset, and the null probe must be demagnetized before the field control can be re-established.

In the new design the drift problem was overcome by using new, more stable amplifiers, high-quality selected resistors and a well-regulated power supply. The remaining problems were solved with basic design changes. The original design externally programmed only the power supply which supplied current to the reference solenoid. Thus the integrator had to provide the total external programming voltage to the spectromagnetic power supply. One innovation of the new design was to provide to the Spectromagnetic supply a programming voltage proportional to the channel number. Consequently the integrator need only provide a voltage to offset the non-linear permeability effects due to the iron in the spectrometer. Since the necessary integrated error voltage now is much less than that previously required, the stabilization time is reduced. The stabilization time was further reduced, and the stability of the system was increased, by the addition of an amplifier in parallel with the integrator. The long term stability of the new system is measured by the root-mean-square (rms) deviation of the channel number which is found to focus the leading edge of

the strong ^{137}Cs internal-conversion electron peak. Data were repeatedly collected during a forty-eight hour interval. The rms deviation was less than 2 channels (with a maximum deviation of 20.2 channels.) The stabilization time for a 100-channel step is less than one second for stabilization to within four channel numbers of the steady-state channel number. Finally, the system is stable for current steps of any size. More complete details on the analysis and design of the new stabilizer are given in reference (6).

The reference solenoid used in the field control system was wound from aluminum ribbon and provisions for cooling were designed into the coil by the manufacturer¹. The design specifications for the solenoid were chosen to provide a field of not less than 1200 G at a current of 2.5 A and that temperature effects on the non-linearity of the solenoid would be less than fifty parts per million of the maximum field. The new solenoid does not have the end correction coils used previously (10) to reduce the field gradient at the center of the solenoid. It was felt that these were not necessary since the null probe does not change position once inserted into the solenoid, and that when it is removed and replaced the calibration can be redetermined by simply

¹The reference solenoid was designed and manufactured by Ogallala Electronics, Ogallala, Nebraska.

looking at a conversion line; hence a uniform field over several cm on the central axis is not needed. A small thermistor bead, Fenwal GB31J3, is imbedded in the windings of the solenoid at a position located centrally along the length at approximately the mean radius from the axis. This was done to allow the temperature of the solenoid to be monitored and to allow a protection device to shut down the current supplied to the solenoid if the temperature in the solenoid becomes too great due either to a cooling water loss or an electronics malfunction. A check was made on the solenoid to insure that it did indeed meet the temperature requirements. The measurement used a Rawson-Lush type 924 gaussmeter probe with a 944 gaussmeter indicator, and a Cimron P5900B digital voltmeter. The 944 itself is capable of resolving 100 mG when used with the 924. Using the Cimron P5900B across the output of the 944 allows field changes of less than 10 mG to be resolved.

The procedure followed in the solenoid temperature test was to cut the current to the solenoid and allow the temperature of the solenoid to reach equilibrium with the 19°C water which flows through the cooling system at a rate of 3 liters per minute (lpm). The PDFS was then used to establish a field inside the spectrometer. Immediately after the field stabilized, the field inside the spectrometer was measured and then was monitored as the temperature rose in the

solenoid. Using the thermistor temperature probe inside the solenoid to indicate the increase in temperature, no drift greater than 10 mG was found at a field of approximately 910 G (which corresponds to channel number 325,000 and a current of 1.6 A in the reference solenoid, and is slightly greater than the field needed to focus 8-MeV electrons) for a temperature rise of 9.6°C . While the test did not check the temperature drift at the maximum current of 2.5 A in the reference solenoid, it did show that any temperature effects on the reference solenoid are negligible over the current range which will be used for measurements with the spectrometer.

C. Moving Tape Collector System

1. Principle of operation of the Moving Tape Collector

The Moving Tape Collector (MTC) is a device which is used to provide isobaric separation of radioactivity provided by the isotope separator system. Although the tape collector described here is the first to be used with the beta-ray spectrometer, it is a third-generation tape collector. The first two generations of the MTC were used in gamma-ray studies by the TRISTAN group and are described in references (8) and (11).

The operation of the MTC used with the beta-ray spectrometer can be illustrated with the aid of figure 10. The

Figure 10. Daughter enhancement operation of the MTC

ion beam of a selected mass number is directed into the spectrometer and imbedded in the Mylar tape at point A. In order to enhance the activity ratio of daughter to parent, the following procedure is used. As shown in figure 10, a source is collected at point A for a period T_C ; the tape is then moved until the source reaches point B. Data accumulation for a time T_A begins after a delay period T_D . For parent enhancement shown in figure 11, the source is collected and counted at the ion beam deposition point. After data accumulation, the tape is then moved and a new source collected and counted. A more detailed description of the timing which can be used is presented in the description of the Daughter Analysis System.

2. System design

The MTC system design should reflect several requirements. First the tape movement from point to point must be reproducible to within 2 mm. The tape movement must be directly related to the tape drive mechanism, e.g. the tape should not slip on the capstan drive. To avoid significant activity loss when the tape collector is used with short-lived activities, the tape drive should be capable of moving the tape at a speed of 60 cm/sec.

In the spirit of the final requirement above, the new generation MTC uses 35.6-cm diameter supply reels in place of

Figure 11. Parent enhancement operation of the MTC

the 17.8-cm diameter reels used previously. These reels are conspicuous in the photograph in figure 12 which shows the MTC mounted on top of the beta spectrometer. The new reels give four to five times more tape per reel. This is important because changing 17.8-cm tape reels interrupts an experiment for a minimum of 2 hours due to the outgassing of the newly installed tape. If the tape were run continuously at the high (but not unreasonable) speed of 2.5 cm/sec, the tape supply on a 17.8-cm diameter reel would last less than four hours. Since the beta-ray spectrometer MTC operation will require a 30.48-cm or 60.96-cm length of tape between sources, it is clear that 17.8-cm tape reels are not adequate for experiments involving frequent source changes.

Although the large reels solved the tape supply problem, their large full-load moment of inertia of 0.041 kg-m^2 requires a new and brutish tape transport system. The new tape transport system was also designed with reverse drive capabilities; this allows the tape to be reused without breaking vacuum, a highly desirable feature in light of the discussion above.

The tape may be reused because sources are deposited every 30.48 or 60.96 cm along the tape. After rewind, one can restart the tape at a point midway between the original depositions and run the tape again. After the second time through the tape, the original sources may have decayed away

Figure 12. Photograph of the MTC

sufficiently to allow those deposition sites to be used again.

The tape transport system uses a capstan drive with demand-drive feed and takeup reels (both will be referred to as supply reels) and Constant Tension Arms (CTA's) which keep the tension of the tape constant. The CTA's allow the capstan drive to function properly regardless of the amount of tape on the feed and takeup reels. A sketch of the tape transport system is shown in figure 13. A detailed photograph of the switches and speed controls operated by the CTA's is shown in figure 14. The speed at which the capstan moves is controlled by the MTC translator which has four modes of operation.

In the High Speed Forward (HSF) mode of operation, the feed reel motor is turned on as the CTA is pulled away from the microswitch SW1. The motor speed is determined by the position of potentiometer P1. The potentiometer's position depends on the angular position of the CTA by means of gears as shown in figure 14.

In the HSF mode of operation, as the left hand supply reel arm moves to the right in the figure 14 the speed of the motor increases because tape is not being supplied rapidly enough by the feed reel. Eventually the speed of the feed reel is such that tape is being supplied at the same rate at which it is being moved by the capstan. This steady-state

Figure 13. Schematic view of the MTC

Figure 14. Detail photograph of switches and speed controls operated by the CTA

condition exists until the capstan is stopped. After the capstan stops, the feed reel continues to supply tape, but at a decreasing rate, since the speed of the feed reel decreases as the CTA moves to the left. When the CTA comes to rest against the microswitch SW1 the feed reel motor is shut off.

In the Low Speed Forward (LSF) mode of operation the initial position of the CTA is against SW1 and the feed reel motor is initially off. When the capstan starts moving, the CTA is pulled away from SW1. The feed reel motor is activated when the CTA makes contact with microswitch SW2. At this time the feed reel motor turns at a constant, preset speed which is slightly greater than the speed necessary to feed tape at the rate required by the capstan. The motor continues to run until enough tape has been supplied to allow the CTA to depress switch SW1. This cycle is then repeated as often as required. When the capstan is stopped, the feed reel motor continues to move until the CTA engages SW1.

The two remaining modes of operation of the MTC are High Speed Reverse (HSR) and Low Speed Reverse (LSR) modes. In the reverse modes potentiometer P2 replaces P1 as the motor speed control, and the roles of the switches SW1 and SW2 are reversed. Otherwise, the reverse modes are similar to the corresponding forward modes. The takeup reel system is, as shown in figure 13, the mirror image of the feed reel system. For forward motion of the tape, however, forward mode opera-

tion of the takeup reel is identical to the reverse mode operation of the feed reel.

Slo-Syn bifilar-wound stepping motors were used in the design of the transport system because, when driven by translators designed by the Ames Laboratory Instrumentation Group (ALIG) and adapted for this use, these motors are capable of supplying the high torques at the speeds necessary to operate both the 1.9-cm diameter capstan under the 1.7-nt tension of the tape and the supply reels which, when fully loaded, have a moment of inertia of 0.041 kg-m^2 . The motors operate by alternately routing current through two pair of coils inside the motor. When the motors are not being stepped current flows through one pair only. This arrangement provides stopping and holding torques which allow the tape to be stopped from high speed with a reproducibility of 1.5 mm. This same special characteristic allows the fully loaded supply reels to be stopped rapidly enough so that the CTA's can take up any spillage. A Slo-Syn SS-150 motor is used to drive the capstan through a 7:1 step-up gear ratio, and SS-250 motors are directly coupled to the supply reel drives.

The MTC translators are used to drive the capstan motor and the motors on the two supply reels used in the MTC. The controls of the translators were designed to allow the individual units to be used independently. However, for their primary use, driving the motors of the MTC, all three are

slaved to a master control. This mode of operation is described in Appendix C.

In order to provide a means of relating the number of steps the capstan motor makes to the distance traveled by the tape, one must guarantee that the tape will not slip on the capstan. This guarantee is provided by the CTA's and the pinch roller (labeled PR in figure 13). The pinch roller is a 1.6-cm wide rubber wheel which pinches the tape between itself and the 3/4" diameter, Rexolite¹, capstan. A force of 6.5 nt is required to lift the pinch roller off the capstan.

The moving tape collector also provides the facility to stabilize the isotope beam incident on the tape. Such stabilization is important because any drift in the ion beam position either causes the source to widen, thus reducing resolution, or to shift position, which changes the calibration of the spectrometer. The stabilization is required to correct for changes in the isotope separator acceleration energy and/or changes in the magnetic field of the switch magnet which directs the beam into the spectrometer. Field changes in the spectrometer itself have also been observed to shift the position of the isotope beam inside the spectrometer. In going from zero field to channel 48,000 the beam position was

¹Trademark of American Enka Corporation, Enka, North Carolina.

seen to shift approximately 3 mm. (Channel 48,000 represents a field of approximately 110 G which is roughly the field necessary to force the K-conversion line of the 661 keV transition in the decay of ^{137}Cs .)

The stabilization system makes use of the tape inside the MTC. This tape is 12.7 mm wide and 0.0254 mm thick and has a 0.0089-mm thick layer of aluminum bonded to one side. A groove with estimated dimensions of 0.01 mm depth and 0.3 mm width is ground lengthwise along the center of the tape. Production of the tape is described in Appendix D. This "split" tape then provides two electrically insulated conductors which serve as "stabilizer pins" for the beam position control system.

A current pickoff connects each half of the split tape to the beam stabilization system. The current pickoff is of the design shown in figure 15. The aluminum side of the tape passes over the graphite disks which serve as brushes. These brushes are connected to the inputs of a differential amplifier. The stabilization system then integrates the output voltage of this amplifier and applies the voltage to the external programming input of the switch magnet power supply. This applied voltage causes the current in the magnet to change until the field in the magnet is such that the currents flowing on both sides of the split tape are equal. Two such current pickoffs connected in parallel are used because

the tape contains splices which break the electrical continuity of the tape. The positions of the two sets of pickoffs is shown in figure 13. A close-up view of one pickoff is shown in figure 16.

The existence of the narrow groove in the tape merits discussion. Work by McConnell (12) has shown that the retention of imbedded ions in aluminum is more than 100 times better than that in Mylar; thus, if the activity were to fall on the Mylar, less of the activity would be retained than if it would fall on the aluminum. However, the stable ions which make up the major portion of the beam are slightly separated from the radioactive ions due to small differences in their masses. Thus, when the beam is centered on the tape, the majority of the radioactive ions are incident to the side of the groove. This conclusion is drawn since no differences in activity have been noted for sources which have been collected on both split and solid tapes.

3. The daughter analysis control

The Daughter Analysis Control (DAC) coordinates the operation of the isotope separator beam deflector, the Programmable Digital Field Selector (PDFS) and the Moving Tape Collector (MTC). The DAC determines when activity is directed into the spectrometer, when data accumulation may start, and when the tape should be stepped. The general operation

Figure 15. Current pickoff design

Figure 16. Detail photograph of current pickoff

of the DAC has been described by Olson (8). The system was modified for use with the beta-ray spectrometer, and only two of the four operating modes described by Olson can be used with the beta-ray spectrometer.

The interface of the DAC with the isotope separator beam deflectors allows the deflection of the beam in the isotope separator when a source is not being collected. During the source collection time period T_C the beam deflector is turned off, allowing the ion beam to be deposited on the tape. The interface with the PDPS provides a signal to the PDPS for a period T_A . When this signal is present along with the PDPS signal that initiates the count time, the PDPS program is allowed to proceed with the data accumulation portion of the PDPS program. Finally, the interface with the MTC translator provides a pulse that initiates the movement of the tape at the beginning of the time period, T_M , which is at least as long as the time necessary for the tape to complete its motion. The time period T_D is the delay time between the end of source collection and the beginning of data accumulation.

The signals mentioned above are generated by a program which sequentially counts through four presettable time periods labelled T_1 , T_2 , T_3 and T_4 . The time periods of the interface signals are defined as follows for the mode of operation shown in figure 10.

$$T_C = T_1 + T_2$$

$$T_A = T_2 + T_3$$

$$T_M = T_4$$

$$T_D = T_1 + T_3 + T_4$$

The value of T_4 is selected to be just greater than the time necessary for the tape to complete its motion.

The modification to the DAC mentioned above provides that the time period T_2 be terminated on command from the PDFS instead of waiting for the preset time. This allows the data accumulation time to be completely determined by the PDFS. If this were not the case it would be possible for the tape to start moving before the data accumulation was completed. Setting T_A just greater than the accumulation time set on the PDFS, T_p , is not adequate because of the priority interrupt (described under field control above) which may reset the T_p timer back to zero midway through the period T_A . Furthermore, this modification was necessary to allow the option of taking data at several different field settings for the same source.

For the enhancement of parent activities, the beam deposition point and the spectrometer source point coincide, as shown in figure 11. The DAC is operated with $T_1 = T_2 = 0$, which dictates that data are then accumulated simultaneously with beam deposition. The tape is operated in the fast-forward mode.

For the enhancement of daughter activities, the DAC can be operated with $T_1 = T_3 = 0$, or with only $T_3 = 0$. Timing diagrams for the two cases are shown in figure 17. The diagrams show the time sequence of events at both the beam deposition point (point A of figure 10) and the spectrometer source point (point B of figure 10). In figure 17a the tape is operated at a speed which makes the tape move time T_4 equal to the desired delay time T_D . In figure 17b the tape is moved as rapidly as possible, and T_1 is adjusted to give the desired delay time T_D . A non-zero T_1 increases the collection time, thus increasing the daughter enhancement without sacrificing the data accumulate time T_A or increasing delay time T_D . The mode of figure 17b is, therefore, generally preferable to the mode of figure 17a.

D. Data Collection System

1. Detectors

Several types of detectors are used in the data collection system. A beta detector of new design has replaced the detector originally used (10). This new dual-detector is shown in figure 18. Each section of the detector is a gas-flow proportional detector with end-correction electrodes. The design of each detector is similar to the design of the detector used previously with the exception

Figure 17. Timing diagrams for Daughter Analysis Control
 (a) low duty factor, (b) high duty factor

Figure 18. Cross-section of the dual detector

that the rear detector (the lefthand section shown in figure 18) has no thin Mylar window. The purpose of this windowless detector is to allow background counts to be collected simultaneously with the beta spectra counts. The collection of the background counts makes it possible to monitor the time variation in the background counting rate. The variation in counting rate arises predominantly from variations in source strength and from changes in the environmental radiation level due to neighboring experimenters. The background counts are attributed to the interaction of gamma rays with the detector, mainly through photoelectric processes or Compton scattering. Because of the proximity of the two detectors, the counts seen by the rear detector indicates the background contribution to the total number of counts seen by the front detector which views the focused electrons. The location of the dual-detector inside the spectrometer is shown in figures 6 and 19.

Background correction is accomplished in the following manner. Initially the detector slits are closed and the direction of the field in the spectrometer reversed to insure that no electrons from the source will be seen by the detector. Both the front and rear detectors are allowed to count background for several counting periods T_p while sources are being collected just as they would be under normal data collection conditions. From this procedure, it is

Figure 19. Data collection system

possible to determine the differences in efficiencies of the two detectors and to obtain an initial beta-background reading. To proceed with actual data collection the field is restored to its original direction and the detector slit is opened. The data from the rear detector can be smoothed over several counting periods and then used for background corrections to the beta-spectra data obtained from the front counter.

A NaI(Tl) crystal is used to monitor the activity inside the spectrometer. The location of the 1.9-cm diameter by 5.1-cm long crystal is shown in figures 6 and 19. A graphite filled aluminum can covers the crystal to stop beta rays from the source from reaching the crystal. A 2.5-cm diameter by 45.7-cm long light pipe interfaces the crystal with an EMI 150 UVP photomultiplier tube which is mounted outside the spectrometer. The activity is monitored by setting the window of a Single Channel Analyzer (SCA) about a portion of the spectrum and routing the output of the SCA into a scaler and a ratemeter. This monitor aids in tuning the isotope separator for maximum activity at the source point.

A 6-cm³ Ge(Li) detector placed atop the spectrometer, or a 60-cm³ Ge(Li) detector placed at one of the median-plane ports which looks at the point of deposit, is used to normalize the different sources collected. The gamma-ray spectra from the detectors are analyzed with a TMC

1024-channel analyzer (MCA). An address identifier (built by the ALIG) used with the MCA allows one to digitally set windows on both sides of an appropriate indicator gamma-ray peak and directly about the peak. All events which fall within the two outer windows are counted in a scaler in the data collection system, while counts which fall in the window about the peak are routed to another scaler. For peaks which sit above a continuum which is approximately linear over the region of the spectrum within the SCA windows, the normalized background counts recorded in the background scaler can be subtracted from the counts in the peak-window scaler to obtain the number of counts in the peak. The normalization factor is the ratio of the number of channels in the background windows to the number of channels in the peak windows. For on-line work this normalization scheme can be used for a gamma-ray peak selected in the Ge(Li) spectrum of a parent or daughter activity in the isobaric decay chain. The dead-time corrected information gathered can then be used to correct for variations in the strengths of the different sources collected.

The modified MCA when used with a modified scaler provides data which can be used to correct the gamma-ray data for analyzer dead time. The MCA provides a gate to the modified scaler when the MCA is free to accept counts. The scaler is modified by the addition of a 10MHz oscillator.

When the MCA is free to accept counts, the pulses from the 10MHz oscillator are gated into a two-decade prescaler. The output of this prescaler is then routed into the normal input of the scaler which has a 10^8 counting capability. This allows up to 16.2 minutes of live-time to be counted for each datum point collected.

2. Readout interface

The data collection system makes use of eight readout scalers, seven of which may be interfaced at any one time to the PDFS through the readout interface. The scalers simultaneously record counts from the beta-spectrum detector, the beta-background detector, the Ge(Li) gamma-peak window, the Ge(Li) gamma-background window, the NaI(Tl) activity monitor, the MCA live-time monitor, the counting time interval, and the total elapsed time of the equipment. The last two scalers count pulses from the PDFS which are supplied at the rate of 10 pulses/sec. The beta-spectrum detector scaler is presettable. If the scaler reaches the preset number before the end of the regular counting period T_p , it signals the readout interface which terminates the counting period and then proceeds to read out the scalers. For this mode of operation it is desirable to have the counting-time interval measured in increments smaller than one tenth of one second. A timer which counts milliseconds is used in place of the

scaler which is used to count pulses from the PDFS. This timer is gated on and off along with the scalers which accumulate data from the detectors. The channel number from the PDFS is read out at the same time as the scalars.

The readout interface also has provision for replacing one of the seven scalers with a Cimron P5900B digital voltmeter. The reading of the voltmeter is then read out instead of the information in the scaler. The digital voltmeter can be used to monitor any condition which can be represented by a voltage, e.g., that corresponding to the temperature of the thermistor bead imbedded inside the solenoid.

The readout interface receives a start-data-accumulation signal from the PDFS at the beginning of step two in the PDFS program. The interface then resets and gates on the scalers so they will accept data. The interface gates off the scalers either when the PDFS signals the end of T or when the counts in the beta-spectrum scaler reaches the preset number. After the gate is closed, the interface sequentially reads out the data stored in the scalers onto punched paper tape via a ASR 33 Teletype. After readout is completed, a signal is sent to the PDFS which allows the PDFS to continue its program.

The readout interface has four modes of operation. The normal mode, M0, provides sequential readout of the data from

the scalars onto punched paper tape via the ARS 33 Teletype. At the end of readout, control is returned to the PDFS, and a clock-out pulse is transmitted to the DAC described elsewhere in this thesis. This pulse initiates the collection of a new source in the beta spectrometer.

The M1 mode of operation is used when several sources must be collected to provide adequate statistics for the data collected at a given field setting. In this mode of operation the scalars are interrogated and may or may not be reset at the end of the data accumulation time period T_p . Also at the end of the period T_p a counter, preset to the number of sources required, is decremented. If the counter is non-zero after being decremented, control is returned to the PDFS which repeats step two in the PDFS program. When data have been accumulated the preset number of times, the clock-out pulse is transmitted to the DAC and the PDFS program resumes its normal sequence when control is relinquished by the readout interface.

A mode of operation similar to M1 is M2. In this mode, however, the scalars are not reset or read out at the end of each accumulation period. Additionally, an external signal may interrupt the preset counter and cause readout to occur and end the data accumulation for this field setting. The obvious source of this external signal is the preset counter connected to the beta-spectrum detector.

The final mode of operation is M3 which provides for the case where data may be accumulated from the same source for several different field settings. In this mode, the master mode of operation is repeated the number of times which is set on the preset counter. Each time the master mode is completed the preset counter is decremented. When this counter reaches zero, the readout interface passes the clock-out pulse to the DAC.

III. EXPERIMENTAL INVESTIGATIONS

A. The Decay of ^{85m}Kr

1. Introduction

Several considerations motivated the investigation of the decay of the metastable level of ^{85}Kr . The simplicity of the decay (the decay scheme shown in figure 20) and the strongly converted transition from the metastable to ground state in ^{85}Kr made this a good choice to test the spectrometer for scattering effects. Modifications to the spectrometer had just been completed to eliminate scattering which had been observed previously. Furthermore, the accurate determination of the conversion coefficients in the decay of ^{85m}Kr would allow this decay to be used as a calibration source in calibrating the Si(Li) - Ge(Li) detectors used to study Internal Conversion Coefficients (ICC's) by the Normalized K-conversion Peak-to-Gamma peak (NPG) method.

2. Source preparation

The sources of ^{85m}Kr were collected off-line on aluminized Mylar targets for periods of three to five hours. The target thickness was 0.5 mg/cm^2 . According to work done by Davies et al. (13), 50% of the ions are stopped in aluminum within $14 \text{ } \mu\text{g/cm}^2$, and less than 5% of the ions

Figure 20. Decay scheme of $^{85\text{m}}\text{Kr}$

penetrate deeper than $40 \mu\text{g}/\text{cm}^2$. With these sources, any distortions in the beta spectrum are negligible.

3. Beta-ray measurement and analysis

Because the internal conversion coefficients were determined using the Peak-to-Beta Spectrum (PBS) method, the beta spectrum was measured with the spectrometer operating at 0.2% resolution and 0.5% transmission. The continuous beta spectrum of ^{85}mKr consists of a single allowed beta group. The momentum distribution above $0.45 m_0c$ of the allowed beta group was fit to the theoretical beta spectrum for an allowed beta decay using a least-square computer program. (The beta spectrum below $0.45 m_0c$ is distorted by the proportional counter window) The Electron Radial Wave Function (ERWF) of Bhalla and Rose (14) were used, and corrections for the effects of screening of the nucleus by atomic electrons were made to the ERWF's (15). The expressions used in the analysis of the data were corrected for the effect of the spread of nuclear charge over a finite radius. Such attention to detail is required since the accurate determination of ICC's using the PBS method requires the accurate determination of the intensity of the continuous beta spectrum. Since the data on the conversion electron peaks were collected from the same source as the data on the continuous beta spectrum, the ICC's of the 151.0-keV transition could be determined direct-

ly using the PBS method. The internal conversion coefficients of the 304.5-keV transition were then computed using the relative intensities of the internal conversion electrons found from the data and the relative intensities of the associated gamma-rays found from high-resolution Ge(Li) measurements (16). The intensity ratio of the 151.0-keV gamma transition to the 304.5-keV transition is $(538 \pm 18) : (100 \pm 4)$.

A Fermi-Kurie plot of the beta spectrum above 50 keV is shown in figure 21. Data points coinciding with internal conversion peaks have been eliminated from the plot. The computer analysis gave 840 ± 2 keV for the beta end-point energy and 5.15 as the log ft of the ^{85}mKr beta decay. The uncertainty in the end-point energy includes statistical uncertainties and the uncertainty in the calibration of the spectrometer. The Q-value of the ^{85}Kr beta decay was then calculated to be 687 ± 2 keV.

The data from the internal conversion measurement are shown in figure 22. The coordinates of the two plots are the same, the abscissa is in units of current in the reference solenoid. These units are proportional to the momenta inside the spectrometer. Because of the greater momenta associated with the 304.5-keV transition and the constant $\Delta p/p$ characteristic of the spectrometer ($\Delta p/p = 0.2\%$) the L- and M-conversion lines are not completely resolved for the 304.5-keV transition.

Figure 21. Fermi plot of the beta decay of ^{85m}Kr

Figure 22. Internal conversion spectra of ^{85m}Kr decay
(a) 151.0-keV transition and (b) 304.5-keV transition

The experimental results for the internal conversion coefficients and the K/L/M ratios for the coefficients of the transitions studied are given in table 1. The uncertainties quoted for the 151.0-keV transition include the uncertainties in the intensities of the internal conversion electrons and the uncertainty in the intensity of the allowed beta group. The quoted uncertainty in the 304.5-keV transition is larger than that quoted for the 151.0-keV transition because the calculation for this transition required use of the gamma-ray intensity ratio with which an uncertainty is associated. The theoretical ICC's calculated by Hager and Seltzer (17) are given in table 1. Experiment and theory agree excellently for the K- and L-shell coefficients. The largeness of the experimentally determined M-shell coefficient compared to the theoretical prediction can be attributed to several factors. First the M-shell peak includes conversion electrons from the higher atomic shells. Secondly the uncertainty in the theoretical M-shell calculations is generally greater than for the K- and L-shell calculations, and finally, there is a tendency of the experimentally determined M-shell coefficients to be greater than the theoretical predictions in a large number of internal conversion measurements.

The results indicate that the 151.0-keV transition is purely M1, since the experimental value of 0.040 is just slightly less than the theoretical M1 K-shell coefficient,

Table 1. Internal conversion results for decay of ^{85m}Kr

Conversion	151.0-keV transition		304.5-keV transition	
Coefficient	experiment	M1 theory ¹	experiment	M4 theory ¹
Total	0.0455 ± 0.0009	0.0475	0.509 ± 0.024	0.510
K-shell	0.0400 ± 0.0008	0.0420	0.432 ± 0.020	0.436
L-shell	0.0045 ± 0.0002	0.0047	0.064 ± 0.003	0.066
M-shell	0.0010 ± 0.0001	0.008	0.013 ± 0.001	0.008
K/L/M ratio	89/10/2.2	89/10/1.7	67/10/2.0	66/10/1.2

¹Theoretical internal conversion coefficients taken from Hager and Seltzer (17).

and any E2 mixing would raise the coefficient (the theoretical E2 K-shell coefficient is 0.19). Furthermore it is not uncommon to find experimental ICC's four to five per cent smaller than the theoretically predicted ICC's for a pure M1 transition. Additional support for this conclusion is provided by the exact agreement of the experimental K/L ratio of 8.9 with that predicted for a M1 transition. The theoretical K/L ratio for an E2 transition is appreciably smaller.

For the 304.5-keV transition, excellent agreement was obtained between the experimentally determined ICC's and the theoretically predicted values. In the case of the total, K- and L-shell coefficients agreement was within experimental error. The ICC's for an E5 transition are approximately a factor of two larger than the experimental values obtained. One can therefore conclude that, as with nearly all measured M4 isomeric transitions, the 304.5-keV transition has negligible E5 mixing and can be considered a pure M4 transition.

B. The Beta Spectrum of ^{87}Kr

1. Introduction

The study of the beta spectrum of ^{87}Kr was undertaken at the request of the Nuclear Data Group at Oak Ridge with the goal of resolving discrepancies in reported values of the Beta decay Branching to the Ground State (BBGS) of ^{87}Rb . The

reported values of the BBGS ranged from 15% to 32%, and the reported Q-values ranged from 3.85 ± 0.04 MeV to 3.95 ± 0.05 MeV. As the study progressed it became more and more interesting. A review of the previous works revealed that the intensity ratio of the gamma-ray doublet composed of the 2554.5-keV transition from the level of the same energy, and the 2554.5-keV transition from the 2960-keV level was reported to vary from zero to infinity. The fit to the beta spectrum was sufficiently sensitive to the intensities of these transitions to provide support for the intensity ratio reported by two of the previous five studies.

2. Source preparation

This study was also interesting from the instrumentation point of view. The sources were collected using split tape targets. The targets were 7-cm lengths of split tape described previously in conjunction with the MTC. The targets were mounted at the end of the same source holder which was used for placing sources which were collected off-line into the spectrometer. The tape was oriented to face the ion beam. Two electrical leads connected to the two halves of the split tape were brought out through the top of the source holder, to make possible the use of the switch-magnet beam-position stabilizer during source collection. The sources were made by collecting ions of ^{87}Kr from the TRISTAN isotope

separator on the target for a period of approximately one half-life (78 min.). After collection, the source was oriented with the plane of the source parallel to the radial line through the source position and with the source facing the solid angle defining slits. A delay of several minutes between the end of source collection and the beginning of data acquisition assured that any ^{87}Br and/or ^{86}Br hydride contamination (both with half-lives less than one minute) had decayed away. After the source had decayed to a level of activity which no longer allowed good data to be obtained, the source was reoriented to face the beam again, and a new source was collected on top of the old one. This procedure was allowed since the half-life of ^{87}Rb is 5.0×10^{10} y (18).

3. Beta-ray measurement and analysis

For these measurements the spectrometer was operated at 0.5% resolution and 1% transmission. Ten sources of ^{87}Kr were collected. Each source was counted for a period ranging from two to three half lives. The data from each source was normalized to data taken from a single source which covered six regions equally spaced over the entire momentum spectrum. A consolidated spectrum was computed by taking the weighted average of the ten normalized spectra. The uncertainties in the consolidated spectrum, which ranged from 1.8% at the lower end of the spectrum to 0.5% at the upper end, included

contributions from uncertainties in the individual spectra, background and normalization.

The data from the ten sources were consolidated using the program BSAP. (Appendix A.) The consolidated data were then analyzed with the program SPECT. The fit to the beta spectrum, which used the seven beta group intensities and the Q-value of the decay as free parameters is shown in figure 23. The end-point energy of each beta group was constrained to the value of the Q-value minus the energy of the level in ^{87}Rb , as given in reference (19), fed by the group. The results of the fit are given in table 2 under the column heading "No intensity constraints". The fit gave a Q-value of 3.881 MeV and a variance of fit, χ , (defined as the square root of the least-square sum divided by the degrees of freedom) of 0.927. The BBGS was 30.8% and the ratio of the beta branching to the first excited state to the BBGS was 1.45.

In the "no intensity constraints" fit of table 2 not all of the information available about the level structure of ^{87}Rb was used. In addition to constraining the beta end-point energy differences to the appropriate ^{87}Rb energy level differences, it is also possible to constrain the relative intensities of the beta branches to the excited states of ^{87}Rb . Such intensity constraints utilize the beta feedings to the excited states as reported in the previously

Figure 23. Eight parameter "Free" least-square fit to ^{87}Kr beta decay data

Table 2. Results of least-square fit to ^{87}Kr beta spectrum

Beta group intensities							
Daughter							
energy	No	Intensity constraints from gamma-ray studies					
level	intensity	Reference numbers					Average
(keV)	constraints	(19)	(20)	(21)	(22)	(23)	(19&22)
0	30.80	31.50 (33.0) ¹	33.39 (32.0)	49.91 (13.6)	26.25 (19.6)	23.47 (15.0)	30.52 [0.112] ²
403	44.71	42.02 (40.0)	39.38 (38.0)	24.74 (34.0)	46.61 (49.7)	50.36 (55.0)	42.90 [0.048]
846	5.14	7.11	8.07	7.71	7.73	7.45	7.22
1578	-	0.02	-	0.06	-	-	-
1740	-	0.67	0.99	2.02	0.56	0.46	0.60
2378	-	0.40	-	-	-	-	-
2414	6.72	5.25	4.64	4.98	5.10	5.37	5.07
2555	7.21	8.11	7.23	-	8.39	12.41	8.09
2811	-	0.53	-	-	0.25	-	0.42
2960	4.52	4.04	6.31	10.23	4.64	-	4.27
3055	-	0.09	-	-	-	-	-
3308	0.90	0.28	-	0.36	0.46	0.42	0.91
Q-value ³ (MeV)	3.881	3.882	3.872	3.781	3.915	3.930	3.888
Variance of fit	0.927	1.212	1.290	4.126	1.225	3.495	1.027

¹Branchings quoted in references are given in parentheses²Uncertainties are given in square brackets³Uncertainties in Q-value results are nominally 7 keV

referenced gamma-ray studies of the decay of ^{87}Kr . Fits to the beta spectrum were made using these intensity constraints in addition to the energy constraints. In such fits there are only three parameters, the Q-value, BBGS, and the beta branching to the first excited state; the beta intensities to the other excited states are held fixed relative to that of the first excited state. The application of the maximum number of constraints in this fashion can greatly improve the accuracy of the determination of the Q-value and the BBGS, since the resulting fit is forced into agreement with the daughter level structure information and allows the "lever arm" of the fit to be increased without requiring additional parameters. This is in contrast with the old "Fermi stripping technique", in which the lever arm for the ground-state fit is much shorter and the resulting value of BBGS is much less reliably determined.

When information from more than one gamma-ray study is available, the maximum-constraint fitting technique can be applied using the constraints resulting from each study, and comparison of the resulting fits to the beta spectrum can be used to resolve discrepancies in the studies. Table 2 also gives the results of maximum-constraint fits made using the decay schemes of each of five recent gamma-ray studies (19)-(23). The beta group intensities to the levels reported in each study are shown in table 2; for reference, the values

of BBGS and the beta branching to the first excited state reported in these studies are given in parentheses.

The quantity χ^2 , the variance of the fit, can be used to rate the "goodness" of the fit for each of the maximum-constraint fits. Two cases stand out from the others; the very large values of χ^2 obtained with the intensity constraints from references (21) and (23) are due to the treatment of the gamma-ray doublet at 2556 keV. In the former reference, all of the "doublet" intensity was assigned to the 2960-keV level. The best fit to the experimental data resulted in the reduction of the beta intensity feeding the 2960-keV level from 25% (as reported in reference (21) to 10.2%. At the same time, the BBGS increased from 13.6% to 49.9%. In the latter case, all of the "doublet" intensity was assigned to the 2555-keV level. Here again the value of the BBGS was raised at the expense of the intensities feeding the excited states. In both of these cases the large values of χ^2 are indicative of poor fits to the data due to incorrect assignment of the relative beta branchings to the levels at 2555 keV and 2960 keV. An example of a "bad" fit is shown in figure 24. This fit was obtained using the intensity constraints from reference (21). Contrast this to the fit in figure 23.

The fits obtained using the constraints of references (19) and (22) are slightly better than that obtained using

Figure 24. Least-square fit to ^{87}Kr beta decay data constrained to Omega's results

reference (20). In the latter case, equal intensities were assigned to the components of the doublet, while in the former two cases the ratio of the intensity assigned to the 2555-keV transition to that assigned to the 2557-keV transition was 2.01 and 1.88 respectively. While the fit to the beta spectrum was not sufficiently sensitive to choose between the ratios 2.01 and 1.88, it clearly supports these two ratios over the others reported.

Even though the goodness of fits to the constraints of references (19) and (22) are nearly identical, the fits give significantly different values of the BBGS and Q-value. One final analysis was made which used as constraints the average relative intensities obtained by averaging the intensities of the excited state branchings to the branching of the first excited-state. This analysis yielded the best fit and gave a Q-value of 3.888 MeV and a BBGS of 30.5%.

This value for the Q-value is the same value obtained if one averages the four other best fits. The root-mean-square (rms) deviation in the average is 0.007 MeV. The BBGS obtained using the same averaging process is 30.5% with a rms deviation of 2.2%. These deviations are more realistic than the smaller standard deviations calculated from the least-square fitting process, since they reflect the uncertainties associated with the choice of relative intensity constraints, and are much larger than the calculated standard deviations.

The log ft values for the beta groups were calculated using the best fit values for the BBGS and Q-value. The results differed from the values given in reference (19) by less than 10%.

The data in table 2 can be used to investigate possible spectral distortions due to backscattering from the target tape. The final analysis allowed the intensity of the lowest energy beta group to vary; where in all the other fits this intensity was constrained. The results of the fit reveal a 1.1% increase in the intensity of the beta branching to this level. If this were indicative of backscattering and if the 0.9% branching should really be 0.3% as reported in reference (19), the value of BBGS would increase by 0.6%. This overestimated correction is significantly less than the uncertainty in BBGS, and hence, one may assume that there is no significant contribution to spectral distortions from backscattering from the target tape. Further evidence of the lack of spectral distortions is given by the close agreement of the values of BBGS obtained for the constrained and unconstrained fits. In contrast one can observe the marked disagreement in the direct measurement value of BBGS given in reference (21) and the corresponding constrained value shown in table 2.

During the analysis of the data an attempt was made to verify the spin-parity assignment of $1/2^-$ to the 846-kev

level which was made in references (19)-(23). Due to the large statistical fluctuations in the Fermi plot obtained after subtraction of the higher-energy beta groups from the spectrum, a distinction between the unique and statistical spectrum shapes could not be made. However, the least-square sum in the fit increased from 155 for the fit using a unique shape factor, to 194 for the fit using the statistical shape factor. The fact that the change in the shape factor assigned to a beta group comprising only 5% of the total beta intensity could cause such a change in the least-square sum tends to support the $1/2^-$ assignment which would require a spin change of 2 for the beta transition from the $5/2^+$ ^{87}Kr ground state.

C. The Beta Decay of ^{91}Sr

1. Introduction

The study of the beta and conversion electron spectra for the decay of ^{91}Sr was undertaken in an attempt to determine the character of several of the more intense gamma-ray transitions and to update the previous beta-ray measurements of Ames et al. (24) which were reported in 1953.

The conversion electron spectrum allowed the ICC's to be determined for eight gamma-ray transitions. These ICC's verified the spin and parity assignments made by Knight et

al. (25) to the six ^{91}Y levels involved.

This experiment could not pin down the J^π values of the 1305- and 1580- keV levels in ^{91}Y which Knight et al. had proposed as $5/2^+$ or $7/2^+$. The 652.3-keV transition which de-excites the 1305 level was found to have a M2 multipolarity. Knight et al. had stated that this $7/2^+$ to $3/2^-$ transition to the 652.9-keV level is improbable.

The results of the measurement of the beta branching to the excited states confirm the results obtained by Knight et al. from gamma-ray intensity balances, when the BBGS is correctly adjusted.

2. Source preparation

The sources made for this study were collected by two different methods. For the measurement of the beta continuum, the sources were collected for off-line analysis by imbedding 40-keV ions of ^{91}Kr in aluminized Mylar strips of thickness 0.5 mg/cm^2 and approximately 4-mm wide. The active source areas were 2-mm wide by 25-mm tall. For the internal conversion studies, sources were made on-line by imbedding 60-keV ions of ^{91}Kr in aluminized Mylar targets inside the spectrometer as described for ^{87}Kr sources.

3. Beta-ray measurement and analysis

For the beta continuum studies, the sources were collected for approximately four hours. The data were collected in a single "pass" (or series of counts as a function of spectrometer field) over the continuum. For the internal conversion studies, the sources were collected for approximately nine hours. Because of the small peak-to-continuum ratios of some of the conversion peaks, several "passes" were made over the peaks. Analysis of the data obtained was made using the half-life of 9.48 ± 0.01 h, reported by Knight et al.

The beta spectrum obtained for the decay of ^{91}Sr is shown in figure 25. Also shown in the figure is a six-parameter fit to the data including the five most intense beta groups, obtained using a least-square fitting procedure weighted by the inverse square of the statistical uncertainties. The six free parameters used in this fit were the five beta group intensities and the Q-value. The endpoint energy of each excited-state beta group was constrained to the value of the decay energy minus the energy of the ^{91}Y level fed by the group. The ground-state group was treated using a first-forbidden unique shape factor, with a resulting Q-value of 2.684 ± 0.004 MeV and a ground-state branching intensity of $30.8 \pm 0.5\%$. The data were also

Figure 25. Six parameter least-square fit to ^{91}Sr beta decay data

analyzed with constraints placed on the intensities of all but the ground-state group, as ratios to the intensity of the first excited-state group, determined from the decay scheme of Knight et al. The results of the three-parameter fit were a Q-value of 2.684 ± 0.004 MeV and a ground-state branching of $30.3\% \pm 0.4\%$. The fact that this latter fit, in which the relative intensities of the excited-state beta groups were constrained, is in excellent agreement with the unconstrained fit strongly supports the energy level scheme proposed by Knight et al.

Using the 30.3% ground-state beta branching intensity found in this work and the excited-state beta branching ratios determined from the gamma-ray study of Knight et al., the beta branching intensities in the decay of ^{91}Sr were updated and new log ft values were calculated. The results are shown in figure 26.

The Q-value of 2.864 MeV reported here is 19 keV larger than the value reported by Ames et al. This discrepancy is attributed to differences in the calibration energies used in the two studies. The energy of the isomeric transition in ^{91}Y was independently determined in this work (from the conversion electron peak location in the spectrum) and in the gamma-ray study of Knight et al. to be 555.6 keV, whereas an energy of 551.2 keV was reported by Ames et al. The ratio of the electron momenta of the K-conversion line and the Q-

Figure 26. Level scheme of ^{91}Y

value is the same for the two studies, indicating that the discrepancy is due only to differences in calibration.

The conversion electron spectrum from transitions in ^{91}Y revealed resolved K-conversion lines associated with the 1024.3-keV, and 555.6-keV transitions. The 555.6-keV isomeric transition was exceptionally intense in the conversion electron spectrum and the unresolved L- plus M-conversion lines were also measured. An unresolved doublet was observed for the K-conversion lines of the 272.7-keV and 274.7-keV transitions (hereafter referred to as the 273-keV doublet), and an unresolved triplet was seen for the K-conversion lines of the 652.3-keV, 652.9-keV, and 653.0-keV transitions (to be called the 653-keV triplet below).

The value of the K-conversion coefficient for the 555.6-keV transition was found to be $(4.62 \pm 0.23) \times 10^{-2}$, using the peak-to-beta spectrum method. The total conversion coefficient was determined to be $(5.34 \pm 0.27) \times 10^{-2}$. These results are in excellent agreement with the calculations of Hager and Seltzer (17) for an M4 transition which are 4.59×10^{-2} and 5.43×10^{-2} , respectively. Given the agreement above, the remainder of the internal conversion coefficients were determined by considering only the ratios of the areas of the K-conversion lines of interest to the area of the 555.6-keV K-conversion line, together with the intensities of the associated gamma-rays as reported in reference (25). The

differences in the quality of data obtained are shown in figures 27 and 28 which show the 555.6-keV transition conversion electron peak and the 1024-keV peak, respectively. For the unresolved lines, the conversion coefficients obtained experimentally were compared to an effective internal conversion coefficient, α_{eff} , given by

$$\alpha_{\text{eff}} = \alpha_N \frac{E_N}{G_N} \frac{G_S}{E_S},$$

where

$$G_S = \sum_{i=1}^S G_i$$

and

$$E_S = C \sum_{i=1}^S \alpha_i G_i.$$

In the above expressions, S identifies the unresolved peak, G is the total gamma-ray intensity, E is the total electron intensity, and C is a geometric and efficiency correction factor. The subscript N refers to the normalization peak, which was taken to be the 555.6-keV K-conversion line.

The tabulated results of the internal conversion studies are shown in table 3. The experimental errors in the table include both statistical errors in the intensity of the conversion peaks and the errors in the gamma-ray intensities quoted by Knight et al.

The result for the 749.8-keV transition is closer to the E2 value than to the M1, although appreciable M1 mixing is possible. The 8% experimental uncertainty is large enough to

Figure 27. F-conversion electron peak of 555.6-keV transition in the decay of ^{91}Sr

Figure 28. K-conversion electron peak of 1024-keV transition in the decay of ⁹¹Sr

Table 3. Results of internal conversion measurements in the decay of ^{91}Sr

Transition (keV)	Number of Sources	K-conversion coefficients	
		Experimental	Theoretical ¹
555.6	2	$(4.62 \pm 0.23) \times 10^{-2}$	4.59×10^{-2} (M4)
749.8	3	$(1.08 \pm 0.09) \times 10^{-3}$	1.11×10^{-3} (E2)
			1.02×10^{-3} (M1)
1024.3	2	$(5.51 \pm 0.23) \times 10^{-4}$	5.21×10^{-4} (E2)
			5.18×10^{-4} (M1)
273 (doublet)	2	$(1.25 \pm 0.10) \times 10^{-2}$	2.27×10^{-2} (E2) ²
			1.10×10^{-2} (M1) ²
653 (triplet)	4	$(1.92 \pm 0.15) \times 10^{-3}$	1.14×10^{-3} (E1) ³
			2.02×10^{-3} (M2) ³

¹From Hager and Seltzer (17)

²Multipolarity of 274.7, with 272.7 as M1

³Multipolarity of 652.3, with 653.0 as E1 and 652.9 as M1

make an M1/E2 mixing ratio calculation unfeasible. The 8% uncertainty is due primarily to the errors in the gamma-ray intensities given by Knight et al., since the error in the electron intensity ratio is only 2%.

The measured K-conversion coefficient for the 1024.3-keV transition indicates either M1 or E2 multipolarity, in agreement with the spin-parity assignments of Knight et al. The experimental value, although larger than the theoretical M1, E2 values by slightly more than the experimental error, definitely rules out a parity change transition since the E1, M2, and E3 theoretical coefficients differ by at least a factor of two from the experimental value.

The experimental result for the 273-keV doublet was used to determine the multipolarity of the 274.7-keV component. Table 3 gives the results of the doublet coefficient for M1 and E2 choices for the 274.7-keV transition; in both cases the 272.7-keV transition is taken to be pure M1. The experimental value is reproduced with the 274.7-keV transition having an E2/M1 mixing ratio of 0.11 ± 0.08 and the 272.7-keV transition being pure M1. If the 272.7-keV transition (which comprises 13% of the doublet gamma-ray intensity) is taken to be E2, the conversion coefficient for the 274.7-keV transition is slightly less than the theoretical M1 value. Thus, regardless of the multipolarity of the weak 272.7-keV transition, the 274.7-keV transition is predominately M1, with 11%

or less E2 mixing.

The 653-keV triplet proved to be most interesting. The γ level scheme shown in figure 26 indicates that the 653.0-keV component (which comprises 4% of the triplet gamma-ray intensity) is definitely E1. The 652.9-keV transition occurs between levels of negative parity and could be either M1 or E2. The 652.3-keV component (with 26% of the triplet intensity) would be E1 or M2 if the 1305.4-keV level is $5/2^+$, $7/2^+$ as suggested by Knight *et al.*

Table 3 gives the results of the triplet coefficient for E1 and M2 choices for the 652.3-keV transition; in both cases the 652.9-keV and 653-keV transitions were respectively taken as M1 and E1. As is evident from the table, the M2 choice for the 652.3-keV transition is supported by the data.

Instead of calculating the 653-keV triplet conversion coefficient as in table 3, the experimental result can be used to calculate the conversion coefficient for the 652.3-keV transition. With the 652.9-keV and 653-keV transitions taken respectively as M1 and E1, a coefficient of $(3.54 \pm 0.69) \times 10^{-3}$ is obtained for the 652.3-keV transition, in good agreement with the theoretical M2 value of 3.93×10^{-3} and in strong disagreement with the theoretical E1 value of 0.57×10^{-3} . (A decrease of 8% in the relative intensity of the 652.3-keV gamma-ray, well within the experimental uncertainty of 23% from reference (25) is sufficient to make the

calculated conversion coefficient identical to the theoretical M2 value.) The calculated $3.54 \pm 0.69 \times 10^{-3}$ coefficient corresponds to an E1/M2 mixing ratio of 0.13 ± 0.23 . The conclusion that the 652.3-keV transition is mainly M2 is not changed if the 652.9-keV transition is taken as E2; in this case the calculated coefficient is $2.98 \pm 0.66 \times 10^{-3}$, corresponding to an E1/M2 mixing ratio of 0.39 ± 0.29 .

D. The Beta Spectra of ^{88}Kr and ^{88}Rb

1. Introduction

The endpoint energy of ^{88}Rb was measured to provide a high energy calibration source for the beta-gamma coincidence investigations which have been done by the TRISTAN group. A comprehensive study of Q-values for the fission products studied by the TRISTAN group has recently been carried out by Clifford (26) and Adams (27). The study was made by beta-gamma coincidence measurements using a well-type plastic scintillator and a Ge(Li) detector. The range of these measurements is limited by the range of energies of calibration sources. Up to the time of this investigation of the ^{88}Rb beta spectrum, the highest energy beta calibration source was ^{36}Cl with an endpoint energy of 4.913 MeV. The measurement of the ^{88}Rb endpoint energy increased the range to 5.338 MeV.

The shorter half-life of ^{86}Rb (18 min) with respect to the parent ^{86}Kr (2.77 hr) does not allow the separation of the two nuclei during a measurement of these activities; hence, the beta spectra of both ^{86}Kr and ^{86}Rb were measured.

Finally, the study of the conversion electron spectra associated with the 166- and 196-keV transitions in ^{86}Rb was undertaken at the request of R. L. Bunting after his failure to detect conversion electrons with a Si(Li) detector (5). The relative insensitivity of the beta spectrometer to the gamma rays from the source compared to the Si(Li) detector allowed these conversion electron spectra to be measured.

2. Source preparation

The sources were collected in the manner described previously. Because of the half-lives involved, isobaric separation could not be accomplished, so equilibrium sources were prepared by delaying data collection for two hours after the end of source collection. The ratio of activities as a function of time after collection can be shown to be

$$\frac{A_{\text{Rb}}}{A_{\text{Kr}}} = \frac{\lambda_d}{\lambda_d - \lambda_p} (1 - e^{-(\lambda_d - \lambda_p)t}) - \frac{n_{\text{do}}}{n_{\text{po}}} e^{-(\lambda_d - \lambda_p)t}$$

where

$$n_{\text{po}} = R(1 - e^{-\lambda_p T})$$

and

$$n_{\text{do}} = R(1 - \frac{\lambda_d}{\lambda_d - \lambda_p} e^{-\lambda_p T} + \frac{\lambda_p}{\lambda_d - \lambda_p} e^{-\lambda_d T})$$

represent the parent and daughter activities at the end of the source collection period T which has proceeded at a uniform rate R . The decay constant of ^{86}Kr and ^{86}Rb are λ_p and λ_d , respectively. A plot of the parent and daughter activities and their ratio for different collection periods, T , as a function of time is shown in figure 29. For times long after source collection ceases, the equilibrium activity ratio is

$$\left(\frac{A_{\text{Rb}}}{A_{\text{Kr}}}\right)_{\text{eq}} = \frac{\lambda_d}{\lambda_d - \lambda_p}$$

3. Beta-ray measurement and analysis

Five sources were used in the measurement of the beta continuum. The first four sources gave data which covered the complete momentum range except for the region from 5.49 to 6.44 m_0c . The fifth source covered the complete spectrum except for a range of momenta from 1.84 to 2.54 m_0c . The data from the fifth source were taken with better spectrometer resolution. The 196-keV K-conversion electron peak was also measured at the same spectrometer settings. This was done to allow the conversion coefficient to be calculated using the PBS method. Because of difficulties encountered in fitting the beta continuum, the PBS method was abandoned. Instead, a measurement of simultaneous beta-gamma singles was made to allow an NPG calculation of the K-conversion coeffi-

Figure 29. Relative activities of ^{89}Kr and ^{88}Rb during and after collection (a) normalized activity (b) activity ratio

cients of the 166- and 196-keV transitions.

The data from the first four sources were normalized to the fifth source and consolidated using the program BSAP. The missing momentum range data in the first four sources were supplied by using data from source five. No other data from source five were used in the consolidation. This procedure maximized the number of data points from each set used in normalization. A second consolidation was made using data from one of the earlier sources to fill in the missing data in source five.

The data obtained could not be fit well using the intensity and excited-state energies of Bunting. The best fit obtained is shown in figure 30. This seven-parameter fit had a variance of 1.51. The fit is definitely high in the $5.5 m_0c$ region and low in the valley around $2.0 m_0c$. Furthermore it was necessary to allow an additional low-energy group of significant intensity in the fit. An additional source was collected to check the results; however, a new uranyl stearate target had been placed in the neutron beam and there was ^{87}Kr hydride contamination in excess of 25%. These new data, while not resolving the problem of the fit to the total spectrum, provided another measurement of the ^{88}Rb Q-value since the Q-value of ^{87}Kr is sufficiently far below that of ^{88}Rb to allow the uncontaminated portion of the ^{88}Rb spectrum to be analyzed. The values obtained from the three different

Figure 30. Seven parameter least-square fit to $^{88}\text{Kr} - ^{88}\text{Rb}$ data

consolidations are 5.333, 5.342 and 5.339 MeV, in the order in which they were described above. The average value is 5.338 MeV with an rms uncertainty of 2 keV. This uncertainty is thought to be an upper bound since results of various consolidation attempts and differently applied constraints generally varied within this limit.

The data used to calculate the internal conversion coefficients for the 196- and 166-keV transitions in the decay of ^{88}Kr were taken from two sources; the average value of the ratio of the areas of the K-conversion peaks of the 196- and 166-keV transitions was determined from these two sources to be 5.49 ± 0.16 . The weights used were the reciprocals of the square of the uncertainty of the areas of the peaks calculated by BSAP. Using the relative gamma-ray intensities of Bunting, the ratio of the K-conversion coefficients is 0.67 ± 0.04 . Calculations based on data from these two sources show the average K/L ratio for the 196-keV transition is 8.44 ± 0.50 . This K/L ratio indicates that the 196-keV transition is mainly of M1 multipolarity with an E2 mixing ratio of 0.36 ± 0.64 . The large uncertainty in the mixing ratio is a result of the small difference between the K/L ratios for the M1 and E2 multipolarities.

The second source was also used to obtain simultaneous beta-gamma singles on the 196-keV K-conversion peak. The K-conversion coefficient of the 196-keV transition was calculated

ted from the formula

$$\alpha_K = \frac{A_e}{A_G} \frac{C_E}{C_S}$$

where α_K is the calculated conversion coefficient, A_e is the area of the K-conversion peak, A_G the area under the associated gamma-ray peak, C_S is the geometry correction factor and C_E is the efficiency correction factor. The factor C_E was the product of a factor from the relative photopeak efficiency curve of the Ge(Li) detector and a factor calculated for the absorption of gamma rays as they passed through the 1/2" plexiglas window of the spectrometer. This absorption factor was calculated by using $C_5H_6O_2$ (28) as the representation for the "average plexiglas molecule" and total mass absorption coefficients for carbon, hydrogen, and oxygen (29).

The geometry factor C_S was determined from 304.5-keV K-conversion line in the decay of ^{85m}Kr . Here

$$C_S = \frac{A_e}{A_G} \frac{C_E}{\alpha}$$

The result was $C_S = 111.0 \pm 9.3$. The uncertainty was calculated from error propagation using the uncertainties in all the factors.

The measured value of the 196-keV transition K-conversion coefficient was 0.044 ± 0.004 . This result is characteristic of E2 multipolarity with an M1 mixing ratio of

0.85 $\pm$ 0.26. This result, coupled with the K-conversion coefficient ratios mentioned above, gives a K-conversion coefficient for the 166-keV transition of 0.029 $\pm$ 0.003. The results of the calculations are shown in table 4. The measured values of the K/L ratio and the K-conversion coefficient of the 196-keV transition indicate M1-E2 mixing. It should be noted that the ICC ratios calculated are independent of all gamma-ray work done in this experiment and use the well-determined intensity ratios of Bunting; hence they are considered to be more reliably determined than is the 196-keV K-conversion coefficient. The value of 0.029 $\pm$ 0.003 for the K-conversion coefficient of the 166-keV transition is only slightly less than the value 0.033 predicted by Hager and Seltzer for an M1 transition (17). The ICC values obtained in this work for the 196- and 166-keV transitions confirm the J^π assignments conjectured by Bunting for the 196- and 29-keV levels of ^{88}Rb .

E. On-Line Internal Conversion Electron Measurements

1. Introduction

The measurement of several conversion lines allowed the on-line use of the spectrometer system to be tested and at the same time provided some information on conversion electron spectra not previously determined in the decays of the

Table 4. Results of conversion coefficient measurements of the decay of ^{88}Kr

Internal Conversion Transition	Measured Coefficients	Theoretical Coefficients ¹						
		E1	M1	E2	M2	E3	M3	E4
196 K	$0.044 \pm .004$	0.012	0.021	0.071	0.13	0.37	0.68	1.81
196 L	$0.005 \pm .001$	0.001	0.002	0.009	0.016	0.064	0.10	0.50
196 K/L	$8.44 \pm .50$	9.75	9.17	8.01	8.33	5.68	6.58	3.62
166 K	$0.029 \pm .003$	0.019	0.033	0.13	0.22	0.76	1.38	4.18

¹Theoretical internal conversion coefficients taken from Hager and Seltzer (17).

90, 91 and 92 isobars. Simultaneous beta-gamma singles spectra were accumulated to allow conversion coefficients to be calculated by the NPG method.

2. Source preparation

The sources were prepared by collecting equilibrium sources of a particular isobar. Data collection occurred during source collection, but was initiated only after a delay sufficient to insure that both the Kr and Rb activities were in equilibrium. The tape in the MTC was moved and a new collection began frequently enough to insure that the longer-lived Sr and Y activities were negligible. Any fluctuations in source strength were monitored using the count rate from the windows in the address identifier; these windows were set about the gamma-ray peak associated with the conversion peak being measured. The 60-cm³ Ge(Li) detector was used as the gamma-ray monitor. If a large change in source strength was observed, the tape was moved and data accumulation restarted; thus only small fluctuations in the parent-daughter equilibrium were tolerated.

3. Measurement and analysis

Data were accumulated for the beta-ray spectrum points, the gamma-ray window counts and the live-time counter contents. Each individual conversion peak datum was corrected

for source intensity fluctuations using the information from the gamma-ray windows and live-time monitor. At the end of the scan over the conversion spectrum, the gamma-ray spectrum which had also been accumulating in the MCA was read out. This allows one to study the gamma-ray peak and window settings to verify that the counts in the peak-window scaler are representative of the gamma-ray area or to correct for improper choice of window settings, provided no gain shifts occurred during the scan. Along with the two peak areas and the gamma-ray counting rate to which the conversion electron data were normalized, a geometry correction factor is needed. This geometry factor was measured by collecting data in the same manner on a transition which has a well-known conversion coefficient. The 304.5-keV isomeric transition in the decay of ^{85}Kr was used for this purpose. As reported in an earlier chapter, the ICC for this transition has been measured quite accurately.

The results of the on-line internal conversion measurements are given below. They may be compared to the calculations of Hager and Seltzer in table 5.

Decay of ^{90}Kr : The decay of the mass 90 isobar yielded very interesting results. The most prominent feature of the conversion electron spectrum obtained was a doublet consisting of the K-conversion electrons of the 120.7- and 121.6-keV transitions. The resolved conversion electron

Table 5. Theoretical internal conversion coefficients

Parent Nucleus	Energy (keV) & Shell	Theoretical conversion coefficients ¹						
		E1	M1	E2	M2	E3	M3	E4
⁹¹ Rb	93.6K		0.172	1.09	1.85	8.89		
⁹⁰ Kr	106.9K	0.0697	0.106	0.648	0.780	4.96	8.84	36.3
⁹¹ Kr	108.8K	0.0661	0.101	0.607	0.775	4.95	8.17	33.2
⁹⁰ Kr	120.7K	0.0487	0.0766	0.417	0.730	2.95	5.23	20.0
⁹⁰ Kr	121.6K	0.0477	0.0750	0.406	0.714	2.86	5.07	19.3
⁹² Kr	142.4K	0.0300	0.0490	0.229	0.366	1.45	2.60	8.83
⁹⁰ Rb	93.6L		0.0196	0.182	0.27	3.36		
⁹⁰ Kr	106.9L	0.0076	0.0120	0.0975	0.143	1.47	1.20	22.6
⁹¹ Kr	108.8L	0.0072	0.0114	0.0906	0.134	1.33	1.59	20.1
⁹⁰ Kr	120.7L	0.0053	0.0086	0.0547	0.091	0.767	0.966	10.3
⁹⁰ Kr	121.6L	0.0052	0.0084	0.0580	0.088	0.7371	0.933	9.81
⁹² Kr	142.4L	0.0032	0.0054	0.0310	0.049	0.323	0.440	3.59

¹Theoretical internal conversion coefficients taken from Hager and Seltzer (17).

peaks are shown in figure 31. The presence of the unresolved 106.9-keV L-conversion peaks can be observed just below the 120.7-keV K-conversion peak. The dashed lines indicate the leading (high-momentum) edges of the two peaks. Since the energy difference, and hence the momentum difference, between the two peaks is known, the intercept of the 120.7-keV line was placed with respect to the well-defined intercept of the 121.6-keV line. The slopes of the dashed lines are proportional to the height above the beta-ray continuum for the two peaks. It is encouraging to note that the skewness on the low momentum side begins at the same relative height for both peaks.

Data from three sources were collected. The relative gamma-ray intensity ratio of the 120.7- to 121.6-keV transitions was quoted to be 0.118 ± 0.010 by Duke (30). The rest of the data necessary for the following calculations were measured during the course of the experiment. Two sources were used to accumulate data on both the 106.9-keV and 121-keV doublet K-conversion peaks in order to determine the ratios of the areas of these peaks. The results were 14.35 ± 0.76 and 14.76 ± 0.64 for the 121-keV doublet to the 106.9-keV ratio. It should be noted that the 106.9-keV level is a metastable level with a half-life of 251 seconds and care must be taken to delay data collection until the activity of the metastable level reaches its equilibrium value.

Figure 31. Resolved K-conversion peaks in the 121-keV doublet in ^{90}Kr

The source had been collecting for longer than an hour before the 106.9-keV K-conversion electron spectra were taken. Data from the two spectra with the best resolution were used to determine the ratio of the area of the 121.6-keV to 121-keV doublet K-conversion peaks. The results were 90% and 91% with uncertainties of approximately 0.5% which reflect the uncertainties in calculating the area of the incompletely resolved 121.6-keV peak of the doublet. The intensity of the 106.9-keV gamma-ray transition relative to the 121-keV doublet was determined from gamma-ray spectra taken using the 60-cm³ Ge(Li) detector with a source-detector configuration identical to that of the simultaneous beta-gamma singles measurements. These spectra, as well as the previous spectra, were collected using an equilibrium source.

The gamma-ray singles data allowed the ratio of the area of the 121-keV doublet peak to the area of the 106.9-keV peak to be determined with good statistical accuracy; however, the first measurement gave the ratio as 93.05 ± 4.8 , the second as 77.61 ± 5.2 . The disparity in the two numbers is much larger than the experimental uncertainties. Such an effect could be explained by the presence of a longer-lived contamination which could not be resolved from the 106.9-keV gamma ray. The plausibility of this argument is strengthened by the presence of an unidentified conversion peak seen just below the 106.9-keV K-conversion peak, as shown in figure 32.

Figure 32. The resolved K-conversion peaks of the 106.9-keV and unknown transitions in ^{90}Kr

Since the unidentified peak could be a L-conversion peak, a scan was made in the region below the unidentified peak. The scan showed that there was no peak which could be identified as the K-conversion peak associated with the unidentified peak. This leads to the tentative conclusion that the unidentified peak is a K-conversion peak. There are no gamma rays reported in Kr or Rb isotopes of masses 89 or 90 corresponding to this peak. If the associated gamma ray were seen in a Kr decay the energy would be approximately 106.0 keV, assuming the peak is a K-conversion peak. If it occurred in the Rb decay the energy would correspond to 106.9 keV, which is identical to the ^{90}Rb energy. Attempts to find the gamma-ray peak using a 0.6-cm³ Ge(Li) Low-Energy Photon Spectrometer (LEPS) with a resolution of 0.65 keV proved fruitless.

The ratio of the K-conversion coefficients of the 121.6- and 120.7-keV transitions was found to be 1.16 ± 0.18 from the ratio of the measured areas of the K-conversion peaks and the ratio of the relative gamma-ray intensities. The two measurements of the K-conversion coefficient for the 121.6-keV line gave 0.32 ± 0.04 and 0.72 ± 0.10 . No explanation for the large discrepancy has yet been found. It can be pointed out that the first value lies within the range of the M1-E2 values and that neither make it into the M2-E3 range. The same can be said for the L-conversion coefficients of the 120.7-keV transition, which were 0.28 ± 0.03 and 0.62 ± 0.09 .

respectively.

Because of the anomalous results from the measurement of the ratio of the gamma-ray intensities of the 106.9-keV to 121-keV doublet, no value will be given for the K-conversion coefficient of the 106.9-keV transition; however, from the relative electron intensity ratio, the ratio of the 121.6-keV K-conversion intensity to that of the 106.9-keV, is well determined to be 12.93 ± 0.62 . This incomplete result must stand until further gamma-ray work can unravel the mystery of the gamma intensity ratios of the 121-keV doublet and 106.9-keV transitions.

Decay of ^{91}Kr : Two separate sources were used in the measurement of the 108.8-keV K-conversion coefficient. The 108.8-keV L-conversion line was also observed but sufficient statistics were not obtained to make a K/L ratio calculation feasible. A value of 0.412 ± 0.024 was obtained for the K-conversion coefficient, which indicates a multipolarity of E2 with a M1 mixing ratio of 0.63 ± 0.09 . This result was based on data from the first of the two sources. During the collection of the second source a noise problem was encountered in both the control and data-acquisition electronics during the last half of the run. The source strength varied by a factor of two according to the recorded data, a most unlikely occurrence in view of past experience. Although the calculation for the second source was considered to be

unreliable, the resulting K-conversion coefficient was consistent with M1-E2 mixing.

Decay of ^{91}Rb : The 93.6-keV K-conversion line was the strongest line observed in any of the equilibrium sources collected. After working with off-line sources of low specific activity, such a count rate is something to behold, even though it is expected! Both the K-conversion coefficient and the K/L ratio were measured. The results are ambiguous at best and are theoretically unsound at worst. The value for the K/L ratio was 6.42 ± 0.58 . The theoretical predictions are 8.80, 5.99, 6.85 and 2.64 respectively for the M1, E2, M2 and E3 multipolarities. Since the experimental value is consistent with either E2 or M2 multipolarities, the character of the transition cannot be determined by the K/L ratio. The K-conversion coefficient was measured to be 4.16 ± 0.46 . This definitely lies in the realm of a M2-E3 mixing.

This result, which suggests the presence of a low-lying negative parity level in ^{91}Sr , merits comment. The ground state of ^{91}Sr is $5/2^+$ which is explained by the spin of the odd particle, a $2d_{5/2}$ neutron. Since ^{91}Sr has a closed proton subshell, the lower excited states are expected to consist of seniority-three couplings of the three $2d_{5/2}$ neutrons outside the closed N=50 shell. Thus no parity-changing transitions should be expected between low-energy levels in ^{91}Sr . The lowest negative-parity levels expected would involve a

proton particle-hole, with a $1g_{9/2}$ particle and either a $2p_{3/2}$ or $1f_{5/2}$ hole. Such negative-parity levels would likely have excitation energies of about 2 MeV. If the 93.6-keV transition originates from a level at 93.6-keV, as reported by Duke (30), then a multipolarity of M2 would be very difficult to interpret. If, on the other hand, the 93.6-keV transition connected higher excited levels, such a parity changing transition would not be unexpected. However, the placement of the 93.6-keV transition from a level at 93.6-keV to the ground state is suggested strongly for the fact that the 93.6-keV transition is the most intense in the decay. The possible resolution of this apparent conflict will have to await further investigation on the gamma-ray decay scheme.

Decay of ^{92}Kr : The 142.4-keV K- and L-conversion lines were measured in the decay of ^{92}Kr . Two sources were collected. The first source gave a K-conversion coefficient of 0.123 ± 0.008 and a K/L ratio of 5.64 ± 0.87 . The second source yielded data only on the K-conversion coefficient, which was determined to be 0.133 ± 0.007 . The average K-conversion coefficient was found to be 0.128 ± 0.006 . The 0.128 result would indicate a M1 multipolarity with an E2 mixing ratio of 0.69 ± 0.10 . This result is consistent with the findings of Malmskog and McDonald (31) who determined the transition to be mostly M1 through a measurement of the lifetime of the 142-keV state of ^{92}Rb . It should be noted

that the K/L ratio is lower than that of either the M1 or E2 transitions, which are 9.1 and 7.38, respectively. One should also note the large uncertainty of the K/L value. This uncertainty was a result of the poor statistics in the L-conversion peak data which prevented an accurate determination of the beta-ray continuum.

IV. SUMMARY

The on-line operation of the beta-ray spectrometer has been made a reality. There are no apparent basic problems existing with the total on-line system. The field control system has proven to be adequate and dependable. The moving tape collector is operating successfully. The data collection system is operating as expected.

The on-line system allows undistorted beta-continuum and high-resolution conversion-electron data to be collected on short-lived nuclei which had previously been inaccessible to such study. The dependable nature of the system allows a maximum amount of time to be spent on data collection and the analysis and interpretation of the data collected. The successful development of the on-line system is perhaps a more important contribution to nuclear physics than the contribution of the experimental results summarized below.

The measurement of the K-conversion coefficient of the 304.5-keV transition in the ^{85m}Kr decay has provided a useful calibration source for both simultaneous Si(Li)-Ge(Li) electron-gamma singles measurements of conversion coefficients and electron-gamma singles measurements made with the beta-ray spectrometer and the 60-cm³ Ge(Li) detector. The excellent fit to the beta continuum of this decay was a further indication that the spectrometer did not introduce

spectral distortions, such as from scattered electrons. Both the 304.5-keV K-conversion peak and the measured endpoint have served as calibration energies for the beta-gamma coincidence work carried out by the TRISTAN group (26,27).

The study of the ^{87}Kr beta continuum spectrum resolved discrepancies in previously reported value of the endpoint energy and beta branching to the ground state. The measured endpoint energy was 3.888 ± 0.007 MeV with a BBGS of $30.5 \pm 2.2\%$. These measurements also marked a milestone in the development of the on-line operation of the beta-ray spectrometer. The measurements were the first to be made using stabilized beam collection inside the spectrometer. Segments of the "split" tape were used as targets, and stabilization was accomplished in the same manner as required for on-line operation of the moving tape collector.

The study of the decay of ^{91}Sr served to update beta measurements done in 1953. The new measurements indicated a BBGS of $30.3 \pm 0.4\%$, and an endpoint energy of 2.684 ± 0.004 MeV. In addition conversion coefficients were deduced for the resolved K-conversion peaks of the 555.6-, 749.8-, and 1024-keV transitions. On the basis of both the K-conversion coefficient measurement and the K/L ratio of the 555.6-keV transition, confirmation of its M4 multipolarity was made. The 749.8-keV transition is a mixture of E2 and M1 however, no mixing ratio was calculated because of the large uncer-

tainty in the measurement. A doublet at 273-keV and a triplet at 653-keV were studied. The stronger, 274.7-keV component of the doublet was found to be M1 with a maximum mixing ratio of 0.11 ± 0.08 , if the 272.7-keV transition is assumed to be E2. For a M1 choice for the 272.7-keV transition, the 274.7-keV transition appears to be pure M1. The 652.3-keV transition was measured to be nearly pure M2 assuming the 652.9-keV and 653-keV transition are M1 and E2, respectively. The 1024.3-keV transition is either of M1 or E2 multipolarity.

The ^{88}Rb endpoint energy was measured to be 5.338 MeV. This source can now be used as a calibration source for beta-gamma coincidence measurements. The 196- and 166-keV transitions in ^{88}Kr were found to be M1-E2 and M1, respectively. The BBGS of the Rb decay could not be determined at this time.

The first on-line measurements made using the moving-tape collector and split-tape stabilization were of conversion coefficients. In the decay of ^{90}Kr , two determinations for the K-conversion coefficient of the 121.6-keV transition resulted in values of 0.32 ± 0.04 and 0.70 ± 0.10 . The cause of this discrepancy has not yet been determined. The 121.6-keV K-electron peak was found to comprise $90.5 \pm 0.5\%$ of the 121-keV K-electron doublet intensity. The ratio of the K-conversion coefficient of the 121.6-keV transition to that of the 120.7-keV transition is 1.16 ± 0.18 . The equilibrium

ratio of the 121.6-keV K-electron intensity to the 106.9-keV K-electron intensity was determined to be 12.93 ± 0.62 .

In the decay of ^{91}Kr , the K-conversion coefficient for the 108.8-keV transition was determined to be 0.412 ± 0.024 .

The K/L ratio of the 93.6-keV transition in ^{91}Rb was measured to be 6.42 ± 0.58 , while the K-conversion coefficient was measured to be 4.16 ± 0.46 .

The study of the 142.4-keV transition in ^{92}Kr revealed the K-conversion coefficient to be 0.123 ± 0.008 , and provided the value of 5.64 ± 0.87 for the K/L ratio.

The technique for on-line measurement appears to be a valid one. The good agreement of K/L ratios and the K-conversion coefficients measured for the decays of ^{88}Kr and ^{91}Kr provides evidence of this. The reproducibility of the measurement of the ratios of the 106.9-keV K-electron intensity to the intensity of the 121-keV doublet and the ratio of the 121.6-keV K-electron intensity to the 121-keV doublet intensity is excellent. The two different measurements were made over one month apart and agreement of the measurements was within the experimental errors.

The beta-ray spectrometer is now ready for on-line use. However, one of the priorities may be the reinvestigation of the ^{88}Kr - ^{88}Rb beta spectrum, which would not require the full capabilities of the system. The next on-line studies may be in the region of $137 \leq A \leq 144$. While the endpoint energies

of several of the beta decays have been measured (27), the BEGS have not been measured directly. There should be many conversion electrons which will appear in the decays in this region and hence, the full resolving power of the spectrometer will be put to use. For these studies, the K-conversion line of the 602-keV pure E2 transition in the decay of ^{140}Cs should allow the geometry correction factor to be rapidly determined.

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Just as a Chinese puzzle has its inconspicuous key which holds the parts together and allows the pieces to exist as a

whole, the TRISTAN group has a member who holds the physical TRISTAN system together. Without the unselfish dedication of John R. McConnell it is doubtful that the polish of the system would ever have been accomplished, much less maintained. His invaluable experience and expertness are ungrudgingly available to the experimenter twenty-four hours a day, seven days a week. There is absolutely no way which I can express my thanks to nor by which I could repay John for the aid and encouragement he has given to me over the past four years.

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VII. APPENDIX A: DATA ANALYSIS PROGRAMS

A. Spectrum Consolidation and Internal Conversion Analysis Program

Basically, the Beta Spectrometer Analysis Program (BSAP) reduces the raw data output from the readout interface of the Programmable Digital Field Stabilizer (PDFS) associated with the TRISTAN beta spectrometer. The program corrects the individual data points for background and half-life (when necessary), and normalizes the corrected data points to account for variations in source strength. There are really two versions of BSAP. The first is used for "off-line" sources, i.e., sources which are collected and then data are taken while the source decays. The second is used for "on-line" data collection where the source is moved after data have been collected only once or a few times. The first version subtracts decaying background from the data and then corrects the net data for source decay. The second version uses data from the beta background detector to correct the data from the main beta detector for background. An option in this version allows the background data to be smoothed over several points before it is subtracted from the data of the main beta detector. The data from different sources are normalized to the difference in the number of counts in the gamma-peak and gamma-background windows of the address identifier

described in section II-D of this thesis. After these corrections have been made the program searches through the data points and consolidates data points with the same channel number by taking the weighted average of the data points. The weights are the reciprocals of the squares of the uncertainties associated with the data points. These uncertainties include the statistical uncertainties in the raw data, uncertainties in the background correction and uncertainties introduced by the normalization process.

After the consolidation has been completed an option allows one to divide the consolidated data points by the associated channel number and to multiply the quotient by the appropriate calibration to obtain a "momentum spectrum". Another option allows the data to be punched on cards and/or plotted.

If the data include a conversion electron spectrum, the program proceeds to calculate the area under an internal conversion peak. This is done by fitting a region on both sides of the peak to a straight line. (The continuum under the peak is assumed to be linear over this small region.) The area under the peak is then calculated by using a trapezoidal summing technique. The area under the continuum is taken as the area under the trapezoid defined by the linear fit to the continuum. This area is subtracted from the total area under the conversion electron peak; the difference then gives the

area of the conversion electron peak.

One version of the program allows one to check the normalization of data from various sources which make up the data. This is done by summing the total number of counts in an individual source and comparing it to the sum of the counts in corresponding channels of the consolidated data. This allows one to correct for errors made in initial normalization.

B. Beta Spectrum Analysis Program

The beta spectrum analysis program, SPECT, is a routine for fitting or calculating continuous beta spectra. It assumes no correction for either the finite resolution of a detector or the backscatter tail of a detector; hence, it is most easily used with the magnetic beta-ray spectrometer data. Data points affected by the presence of conversion electron peaks must be removed. An option allows a choice between two types of analysis.

One choice is a least-squares fitting analysis which fits the beta spectrum to known or assumed beta groups. If the fit is made to N beta groups, there are $2N + 3$ parameters. These parameters include the N amplitude coefficients, the N daughter energy levels, the Q -value, the Fierz interference coefficient and a normalization coefficient which

multiplies all of the beta groups. All these parameters may be independently held fixed or varied. For example, if the gamma spectrum associated with the beta decay is well known, the daughter energy levels may be held fixed, i.e., the end-point energy differences can be constrained to the daughter energy level differences. In this manner the number of free parameters may be reduced by N . Additionally, when the relative beta branchings are known, one can fix the ratios of the beta branchings to the excited states to the beta branching of any one of the excited states. Then the ratio of the beta branching of the ground state to the selected excited state beta branching, and the overall multiplicative factor are allowed to vary. In this manner the number of free parameters is reduced to three. The fitting technique involves the simultaneous fitting of all the beta groups; hence, there is no accumulation of errors as there is in a Fermi stripping analysis.

The Fermi stripping analysis is the second type of analysis that can be performed by SPECT. This technique fits the Kurie-plot of the outer portion of the spectrum (defined by a lower limit, L_{MIN} , and an upper limit, L_{MAX}) to a straight line by varying the amplitude and end-point parameters of the outermost group. The calculated outer group (group I) is then subtracted from the total spectrum, and a Kurie plot of the remainder of the spectrum is made. This allows a choice

to be made as to the portion of the remaining spectrum which is due solely to the group I-1. Fermi-plot stripping can then proceed for the next beta group.

VIII. APPENDIX B: THEORY OF OPERATION OF THE PROGRAMMABLE DIGITAL FIELD SELECTOR¹

A. Definition and Terminology of the Basic Circuit Elements

Band Register (BR) (Figure B1.),

The BR is used to accommodate independent selection of parameters -- lower limit (LL), channel increment (ΔC), time interval (T_p), upper channel limit (UL) -- within each band. It consists of a seven position shift register; positions 1 through 6 enable the respective parameter switches of each band, position 7 (overflow) is used to return the system to its starting position. LOAD BR enables the lowest selected (active) band. ADVANCE BR will step up the register through its higher selected band positions, including overflow. RECOGNIZE RZ band indicates that the counter is in a band position, RZ overflow indicates the overflow state.

Function Register (FR) (Figure B2.),

The FR facilitates the program that is to be executed during

¹The Programmable Digital Field Selector was originally designed by C. H. Weber who was a member of the ALIG. Modifications have been made to the original design to allow its use for on-line work. This appendix is the revised copy of Mr. Weber's description of the theory of operation.

Figure B1. Band register

Figure B2. Function register

operations within a band. Its functions are controlled by the parameter settings of the band which is currently enabled. The functions are:

C: advance the channel register to the lower limit (LL)

TD: system wait period. This period is terminated if there is no error signal after a preset six seconds period. The error signal indicates the field is not within a specified tolerance. The alternative is switch selectable. A switch overrides the six second delay and this function is terminated immediately or after an error signal clears. When the six second delay is chosen TD is called T_6 .

T_p : preselected time interval during which data are to be taken. If a priority interrupt is received during the time interval T_p the TR is halted and reset to zero. When the interrupt clears the TR is started again. At

the end of the time interval T_p , control is transferred to a readout interface. When the interface has completed its task it returns control to the PDFS. It is to be noted that the readout interface can return control by causing the time interval T_p to be repeated. This allows data to be taken repeatedly at the same current setting.

ΔC : advance the current register by an amount as set by the current increment (ΔC).

The FR consists of a 4-position shift counter with internal feedback from position 4 to position 2. LOAD FR establishes function C, ADVANCE FR causes the counter to step through its remaining positions. The ADVANCE FR command that follows position 4 forces the FR back to position 2, thus closing the loop of steps between positions 2 through 4. Upon recognition of the upper channel limit (UL), operations within the loop are terminated and the FR will be reset.

Channel Register (CR) (Figure B3.),

The primary function of the CR is to

- (a) establish initial and final channel settings for each selected band
- (b) allow the channel setting to be incremented as controlled by the CR.

The CR consists of a 6 decade counter with preset logic circuitry to recognize equality between the state of the register and its associated LL/UL switch settings. It will be advanced upon commands as governed by the C or its present state is displayed at the front panel and also transmitted to the Fluke Voltage Calibrator.

Figure B3. Channel register

Channel Increment Register (Δ CR) (Figure B4.)

For operations within a band, it is necessary to increment the CR by an amount Δ C. Whenever this operation takes place, the Δ CR is advanced Δ C increments; simultaneously with the CR, until the preset logic associated with the Δ CR recognizes equality of values between the state of the CR and the Δ C switch settings.

Figure B4. Channel increment register

Time Register (TR) (Figure B5.)

The duration of the functions T_p and T_6 is controlled by a timer with a resolution of 0.1 minute over a range from 0.1 minute to 99.9 minutes. The time-interval T_6 (6 seconds) is fixed by recognizing a signal at the output RZ T_p . (When T_6 is active this time interval must be generated each time a current change takes place, i.e., when the CR is advanced, and it is needed to allow sufficient time to stabilize the current-generator.) The time interval T_p must be switch selected and represents the actual time during which the experimenter can perform measurements on the spectrometer. Preset logic recognizes equality between the state of the TR and the T_p switch-settings.

B. Discussion of the Flow Chart

A simplified logic-flow chart for the system operation is shown in figure B6 and discussed below.

Upon "start" the BR is loaded and the lowest selected band enables its associated switch assemblies. RZ band indicates that an operation within a band will take place.

The next step is LOAD FR, i.e., to establish function C. Function C will cause the CR to advance to the LL of the band. When RZ LL occurs the FR will advance one step to the

Figure B5. Time register

Figure B6. The PDFS logic-flow chart

TD waiting period.

During the TD function, the TR is started and clocks time until RZ TD occurs. RZ TD will step the FR to its next position, T_p . The TR will restart and run until RZ T_p is detected. RZ T_p transfers control to the readout interface.

The task of the readout interface is to readout the data accumulated during the period T_p onto a permanent record. The interface has a preset counter which is decremented each time control is transferred to the interface. If the counter is not at zero after being decremented, the TR is reset and the T_p period is begun again to enable data to again be collected at this field setting. When the counter reaches zero, the FR is advanced.

In the ΔC position, the CR and the ΔCR are advanced together. If during this operation the UL setting of the present band is not detected by RZ UL, both registers will step up until detection of RZ ΔC by the ΔCR preset logic occurs. RZ ΔC will set the FR back to the T_p state, hence starting loop 1 over again. If RZ UL is detected before RZ ΔC occurs, the sequence of steps will exit into loop 2 and clear the FR entirely.

Exiting via loop 2 causes the BR to advance to the next higher band and the process for this band is repeated in the same manner as described for the previous band.

If exiting via loop 2 causes the BR to advance to the overflow state -- operations within all the selected bands are exhausted -- the system enters a home cycle in order to become ready to repeat the entire program.

During a home cycle, the CR is returned to its starting position by one of three switch-selected options.

1. Return the CR to zero.
2. Return the CR to the LL of the first selected band.
3. Step up the CR to full scale and then return it to zero.

The operator will make his choice which is primarily dependent on how much hysteresis of the spectrometer can be tolerated as a trade-off in time to be ready for another run of the program. For on-line operation only options 1 or 2 are used. In figure B6, only method 1 is indicated. Once this cycle is initiated, the CR will be decremented until it is returned to zero (RZ 0), where the direction is reversed again and, depending on the repeat condition, the system will restart.

For simplicity, the other two cycles are not shown in figure B6, but in general, they perform similar operations.

IX. APPENDIX C: MOVING TAPE COLLECTOR TRANSLATOR

The translators are basically variable frequency oscillators which drive a high-current sequencer to route current through the coils of the motor. The basic improvement over the stock translators typically used with these motors is that the supply voltage is nominally three times that used for the stock translators. The maximum current is electronically limited to the maximum rated current of the motors. The reason for the resulting improvement in the operation of the motors is briefly described below.

The coils in the motor can be represented by an inductance L . The resistance of these coils and the current limiting resistor in series with the coil can be represented by a resistance R . Thus, the current in any winding can be described as $I = (V/R) (1 - e^{-Rt/L})$, where t is the time elapsed since current was applied to the winding. For the MTC translators, V is increased by a factor of three. Then,

$$I = V/R \quad \text{for } 0 \leq t \leq T_{\max}$$

$$I = 3V/R(1 - e^{-Rt/L}) \quad \text{for } t \geq T_{\max}$$

since the current is electronically limited to the value V/R . This value is reached after a time $T_{\max}$. It can be shown that the current builds up much more rapidly; in fact, the time necessary for the current to reach $0.9(V/R)$ using

the commercial translators is 6.5 times greater than that for the MTC translators. It is in this manner then that the torque at higher speeds and the maximum speed of the motors is increased.

X. APPENDIX D: SPLIT TAPE PRODUCTION

Production of the split tape utilizes a Unimat Model 1000 lathe, a capstan-drive tape transport, a 2.54-cm diameter stiff bristle brush, a carborundum grinding wheel 2.54-cm in diameter, and requires much patience. The production facility is shown in figure D1. The grinding wheel and tape are shown in more detail in figure D2. The first step in the process is to make the groove in the tape. The carborundum wheel turns at 5,000 revolutions per minute (rpm), and the tape moves at 2.6 cm/sec. Alcohol is applied to the tape above the grinding wheel and moves down with the tape to the grinding wheel. It was found that "dry" grinding is a much inferior process. Brushes on the opposite side of the pivot bar tend to clean the groove and remove excess alcohol. After the grinding step the carborundum wheel is replaced by a stiff bristle brush and the tape is again passed through the system. The brush, which moves with the same rpm as the carborundum wheel, provides further cleaning of the groove. If a short segment of tape is found in which the aluminum is not completely removed from the groove, the groove is completed with a razor blade. Sometimes lengthy segments which are poorly ground are encountered. These segments are cut out and the tape butt spliced together. Since

Figure D1. Photographs of split tape production apparatus

Figure D2. Detail photograph of tape and grinding wheel

this butt splice breaks the conducting path along the tape, two current pickoffs are used as noted above. Hence, one must assure that two splices do not occur in any three-meter segment of the tape since three-meters is the distance traveled by the tape between the current pickoffs.