INTERNAL CONVERSION COEFFICIENTS
IN THE DECAY OF ^{91}Kr

Robert Stephen Weinbeck

Ph.D. Thesis Submitted to Iowa State University

Ames Laboratory, ERDA
Iowa State University
Ames, Iowa 50010

Manuscript Date: November, 1974

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Internal conversion coefficients
in the decay of ^{91}Kr

by

Robert Stephen Weinbeck

A Thesis Submitted to the
Graduate Faculty in Partial Fulfillment of
The Requirements for the Degree of
MASTER OF SCIENCE

Department: Physics
Major: Nuclear Physics

Approved:

Fred H. Wozniak
In Charge of Major Work

R. G. Barwood
For the Major Department

For the Graduate College

Iowa State University
Ames, Iowa

1974

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Internal conversion coefficients
in the decay of $^{91}\text{Kr}^1$

Robert Stephen Weinbeck

Under the supervision of

F. K. Wohn

From the Department of Physics

Iowa State University

The use of a Bartlett-type $\pi/\sqrt{2}$ double-focusing beta-ray spectrometer on-line to the TRISTAN isotope separator at Ames Laboratory for measurements of internal conversion coefficients is described. The K-conversion coefficient of the 108.8-keV transition to the ground state in the ^{91}Kr decay was deduced to be 0.109 ± 0.007 . The K-conversion coefficient of the 93.6-keV transition to the ground state in the ^{91}Rb decay was determined to be 1.10 ± 0.09 . The 93.6-keV K/L ratio was deduced to be 5.95 ± 0.24 . These results are related to earlier studies, and conclusions in terms of the shell model are given.

¹USAEC Report IS-T-654. This work was performed under contract W-7405-eng-82 with the U.S. Atomic Energy Commission.

Distribution:

1	Oak Ridge, Tennessee
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I. INTRODUCTION

Current research in nuclear physics is directed at determining the nature of the strong interaction. This is accomplished by the gathering of all experimental data possible and applying it to evaluate theoretically developed models which have been proposed. As the models become more sophisticated and experimental information becomes more precise and abundant, it is hoped that the emerging picture will approach a closer understanding of the nature of the nuclear force.

Some of the observables which can be used to test proposed theories are the energies of excited nuclear levels, as well as the transitions between these levels, the spins and parities of these nuclear states, and nuclear moments. Excited state energies are easily obtained but are less discriminating between various models. A more definitive test to discriminate between various models is in the use of angular momenta, or spins, and the parities of the states.

Unfortunately, the spins and parities of excited levels can only be deduced by determining the multipolarities of transitions between states. Then, by the use of all available decay information, including the energies and intensities of all decay processes (alpha, beta, and gamma emission, as well as internal conversion processes, which populate and depopulate each level), an energy level scheme can be estab-

lished, and possible spin and parity assignments can be made indirectly. A trivial example might be the formation of a nuclide in an excited state following the beta decay of the parent, an even-even nucleus. Only one gamma ray is observed in the decay, and the internal conversion electron spectrum, to be mentioned later, definitely characterizes the transition. The gamma ray would determine the energy of the excited level. The nature of the beta-decay spectrum could be used to help determine the spin and parity of the excited level, and the internal conversion spectrum is useful to help determine the spin and parity of the ground state. The level scheme can then be compared to the predictions of a nuclear model, such as the shell model.

One very sensitive method of determining multipolarities of nuclear transitions is by measurement of the Internal Conversion Coefficient (ICC) associated with the transition. An excited nucleus, rather than decaying by emission of a gamma ray, may transfer the excess energy to one of its orbital electrons which is then ejected. The ICC of a nuclear transition is defined to be the number of electrons ejected from a particular atomic orbit per quantum emitted (1). The ICC depends on the particular atomic electrons involved, the transition energy and, most importantly, the multipolarity of the radiative transition. Since the wave functions of the atomic orbits are well-known and the nature of the electro-

magnetic interaction is believed to be well-understood, a measurement of the ICC can be a very accurate way to determine the multipolarity. Extensive tables of ICCs are now tabulated (2).

II. REVIEW OF LITERATURE

This study was undertaken to resolve certain inconsistencies which have appeared in the literature concerning the decays of ^{91}Kr and its daughter, ^{91}Rb . The low-lying, first excited levels in ^{91}Rb and ^{91}Sr have been deduced to have conflicting parity assignments in the different studies mentioned below.

Mason and Johns (3) investigated the decay of ^{91}Rb . They deduced a total ICC for the transition from the first-excited state of ^{91}Sr at 93.6 keV, by comparing the intensities of all the gamma rays observed to populate this level, minus those depopulating it, and assuming no excited-state feeding by beta decay. This ICC deduced for the 93.6-keV level provided a lower limit to the actual ICC. The limit of 0.9 ± 0.2 implied that the transition was primarily E2, since a pure E2 transition has a total ICC of 1.3 for this nucleus and energy (2).

Malmskog and MacDonald (4) also investigated the ^{91}Rb decay. They measured the $K/(L+M+\dots)$ ratio and deduced a total ICC for the 93.6-keV transition. The $K/(L+M+\dots)$ ratio was 5.38 ± 0.21 compared with ratios of 4.96, 7.17, and 5.62 for E2, M1, and M2 transitions, respectively. They ruled out the M2 possibility on level lifetime measurements. This ratio then implied a transition which was $(81 \pm 9)\%$ E2, and

had a total ICC of 1.1, in good agreement with the estimate of Mason and Johns.

During the investigation of a series of decays, Halbig (5) obtained preliminary data on the decays of ^{91}Kr and ^{91}Rb . In the decay of ^{91}Kr , he measured the K-conversion coefficient for the 108.8-keV transition. The result, 0.412 ± 0.024 , was consistent with an M1/E2 transition. In the decay of ^{91}Rb , however, the K-conversion coefficient was 4.16 ± 0.46 , consistent with M2/E3 mixing. The measured K/L ratio was 6.42 ± 0.58 . This could have been either E2 or M2. The attempt to verify these results by repeating the measurements led to different answers, although the ratio of the 93.6-keV to 108.8-keV K-conversion coefficients was very reproducible. This lack of reproducibility led to a lack of confidence in the calculated ICC values and a need to repeat the measurements. If the 93.6-keV transition were, in fact, in the M2/E3 range, it would imply that the transition is parity-changing. Since the ground state of ^{91}Sr is well-established to be $5/2^+$ (6), as predicted by the shell model, all low-lying, excited states should consist of configurations of the three $d_{5/2}$ neutrons. Therefore, no opposite parity level should be seen at such a low energy.

Recently, Achterburg et al. (7) have reported the reverse situation from the conclusions of Halbig. By taking simultaneous beta-gamma singles measurements with a Si(Li) -

Ge(Li) detector combination, they have found the 108.8-keV K-conversion coefficient to be 0.067 ± 0.012 and the 93.6-keV K-conversion coefficient to be 1.05 ± 0.10 . This implies that the 108.8-keV transition is E1, i.e. parity-changing, while the 93.6-keV transition is E2. This would place the parity-changing transition in ^{91}Rb rather than ^{91}Sr , which is just as perplexing for the shell model to explain. The shell model predicts a ground state of $5/2^-$ corresponding to a proton hole in the $f_{5/2}$ shell. All other low-lying states should consist of $f_{5/2}$ or $p_{3/2}$ hole mixtures, all negative parity.

It was therefore felt that new measurements of these ICCs should be attempted to determine which value is the correct one. If a parity-changing transition between the lowest excited-level and the ground state exists in either ^{91}Rb or ^{91}Sr , it would present a serious departure from the well-established shell model explanations of low-lying excitations in this region of nuclei.

III. EXPERIMENTAL FACILITY

A. TRISTAN Isotope Separator System

The ICC measurements reported in this study were made using the TRISTAN isotope separator on-line to the Ames Laboratory Research Reactor (8, 9). The layout of the TRISTAN system is shown in figure 1. The reactor is a heavy water moderated and cooled type, using enriched ^{235}U fuel, and operates at a thermal power of five megawatts. A fission product generator, which is an aluminum can containing approximately ten grams of uranium stearate powder on trays within the can, is located in a neutron beam emerging from the reactor. The thermal neutron flux at that point is approximately 3×10^9 thermal neutrons per cm^2 per second.

Emanation of fission products from the generator is significant only for the rare gases, Kr and Xe. Other products are held up in the stearate or transport line and do not reach the ion source. To assist the transport through the 1.7-m transport line, a sweep gas of 98% He, 1% Kr, and 1% Xe is added. This sweep gas also aids in the later identification of beam components and in focusing of a sharp beam profile.

After passing through the transport line, the sweep gas and contaminants are ionized in the ion source. The resulting ions are accelerated through a potential of 50 to 60 kV

Figure 1. Physical layout of the TRISTAN isotope separator facility

before introduction into the 1.6-m radius, 90° sector magnet where mass separation occurs. Since the vast majority of the ions are Kr and Xe, mass separation is effectively isotopic separation of either the Kr or Xe isotopes. The sector magnet provides a dispersion between adjacent masses of about 1.8 cm for the $A = 90$ region at the focal plane in the collector box. There are also two electrostatic lens for focusing of the isobaric beams. The optimum beam profile, as seen in the collector box, is a line about 1 mm wide by 2 cm high.

By adjusting the separator magnet current, the beam of interest is directed to a slot between two plates in the collector box. The plates stop all other mass-separated beams within $\pm 8\%$ of the central mass and allow the desired beam to reach the experimental apparatus. Position stabilization of the beam also occurs here. Two copper pins in the focal plane are used to "straddle" one of the other isobaric beams present. As the separate beams drift, due to variations in magnetic fields or accelerating voltages in the system, a greater amount of current will be deposited on one of the pins than on the other. A proportional correction voltage is applied to the accelerating voltage to realign the stabilization beam symmetrically between the pins, and hence, the desired beam within the slot.

The beam is then directed through a switch magnet which diverts the beam to the desired apparatus. For the experiments in this study, the beam was diverted through 45° to the beta-ray spectrometer. There is also another electrostatic focusing lens located at the switch magnet for beam height adjustments beyond the separator.

B. Beta-ray Spectrometer System

1. Spectrometer design

The beta-ray spectrometer is a $\pi \sqrt{2}$ double-focusing type with an average central radius of 30 cm. This design has been described previously in detail elsewhere (5, 10, 11). The main advantage in the use of a magnetic spectrometer over other types of electron spectrometers, such as a Si(Li) detector, is its better resolution of 0.2%. It is usually operated at a transmission of 0.4%. The improved resolution capability is needed to separate the 93.6-keV L- and 108.8-keV K-conversion lines completely so as to determine the 93.6-keV K/L ratio accurately. This capability is not usually available with a Si(Li) detector.

The spectrometer is of the "inside-out" design as shown in figures 2 and 3. For on-line work, this type is necessary to eliminate effects due to stray magnetic fields and background radiation. By having the electron path enclosed within the magnet coils and iron wall, fringing fields from

Figure 2. Cross-section of the TRISTAN beta-ray spectrometer

Figure 3. Simplified top view of the TRISTAN beta-ray spectrometer

other magnets in the TRISTAN system, especially the switch magnet, can be reduced to acceptable levels. Also, this design aids in shielding the detectors from background radiation, part of which arises from the ion beams which are stopped in the collector box.

2. Field control system

Since a magnetic spectrometer is a single-channel device, that is, during a single counting period, it detects only the electrons emitted within a small momentum interval; it is necessary to employ a field control system to step the spectrometer field through the series of momentum values involved in "scanning" a conversion line or beta spectrum.

The field control system consists of a Programmable Digital Field Selector (PDFS), a reference solenoid, and a field stabilizer. The PDFS, described in detail in refs. 5 and 11, is a hard-wired program which is capable of dividing up the magnetic field range into 500,000 channels. The maximum field corresponds to an energy in excess of 8 MeV. It is possible, with the available switch positions, to designate six bands within a spectrum, each having an upper and lower limit, a channel increment, and a data accumulation time. The banding capability allows one to vary field steps and count times over different parts of the spectrum. While large steps are sufficient to determine background counts above and below a conversion electron peak, small steps are

desirable to accurately evaluate the peak area.

Basically, the field control is accomplished as shown in figure 4. The PDFS controls the Fluke voltage calibrator which supplies a voltage proportional to the PDFS channel setting to the Spectromagnetic current supply for the spectrometer coils, and to the Alpha Scientific current supply for the reference solenoid. The solenoid (from Ogallala Electronics, Ogallala, Nebraska) is a water-cooled, wound aluminum ribbon placed at the 30-cm central radius. Since it is designed to be relatively temperature-independent while its field is directly proportional to the applied current, the solenoid provides a very stable and accurate reference field. The temperature effects on non-linearity of the solenoid are less than 5×10^{-5} at maximum field, while the precision limit due to non-linear effects of the momentum calibration are about 2×10^{-5} (5, 11).

A Hewlett-Packard null probe is located at the center of the solenoid. It senses an inequality between the solenoid and the spectrometer magnetic fields and supplies an error voltage to the field stabilizer. The field stabilizer then adds a correction voltage to the Spectromagnetic power supply for the spectrometer coils. This procedure is necessary since the spectrometer has an iron core. Because of the hysteresis effects of iron, identical coil currents do not always create identical magnetic fields at the electron

Figure 4. Block diagram of magnetic field control system

orbit. Also, the presence of iron adds a non-linearity to the relation between the coil current and the magnetic field.

This system has been shown to stabilize very rapidly after large channel increments, and to be very reproducible in focusing over a long period of time (11). The need for a rapid response time is evident when a duty cycle may require many field changes for a short-lived source or the enhancement of a particular source.

3. Data collection system

The data collection system associated with the spectrometer consists of nine scaler outputs from four detectors, two timers, and the PDFS as shown in figure 5. At the end of a data collection period, a teletype interface interrogates the scalers and prints out the information on an ASR 33 teletype as well as punching it on paper tape. The PDFS scaler readout consists of the channel number.

Electrons in the spectrometer are counted by the beta detector. The beta detector consists of a dual, gas-flow proportional counter with end-correction electrodes. This dual detector is mounted at the focal point inside the spectrometer and is shielded from source gamma rays by lead wedges. A cut-away view of the detector is shown in figure 6. The foreground detector has a 0.006-mm thick, aluminized Mylar window. The background detector is located directly behind the foreground detector. This windowless detector

Figure 6. Cross-section of the dual detector

allows simultaneous counting of the background contribution while foreground counting is in progress. It is then possible to correct each data point individually for background counts.

Before the experimental investigations were begun, a series of measurements were made to determine the best operating parameters for the proportional counter. Measurements were made on the energy response of the detector to the current in the spectrometer coils. Another series of measurements was made to determine the best bias voltage, amplifier gain, and discriminator settings to use. Previously, modifications had been made to the proportional counter consisting of drawing the center electrode to a finer diameter, adding Teflon insulators between voltage connectors and the aluminum housing, and adding a capacitor network to eliminate "cross-talk" signaling between the background and foreground detectors. A ^{137}Cs source was introduced into the spectrometer to provide electrons for counting purposes.

A series of spectrometer coil currents, 0.3 A to 1.08 A, were manually dialed on the Spectromagnetic current supply. (1.08 A is the current necessary to detect the K-conversion line of ^{137}Cs .) The detector output was passed through a pre-amplifier, amplifier, and discriminator before being introduced into the 1024-channel analyzer. The resultant data of peak centroid channel number and upper and lower half-

maximum channel numbers are plotted against the inverse-square current settings in figure 7. The difference of the upper and lower half-maximum channels is defined to be the Full Width at Half Maximum (FWHM). The inverse square of the channel setting was selected as abscissa since this choice of abscissa linearized the data.

A second series of measurements was made to find the optimum values of the parameters for bias voltage, amplifier gain, and discriminator setting. The method used was to fix two of the parameters and collect counts for a given time at one current setting for various values of the parameter of interest. Then the optimum value of that parameter was held fixed, and another was varied. This was repeated until a combination was found where the count rate was relatively independent of small variations of the parameters. For example, the amplifier gains and discriminator settings were fixed while measurements were made at 0.3 A for one minute for bias voltages of 2350 V, 2400 V, and 2450 V. Then measurements were made at these settings for other currents. As operation at 2450 V did not introduce an unusually increased count rate, it was used while various discriminator settings were tried until one was noticeably above the "noise" level of the amplifier.

One other problem was investigated. Earlier data had shown displaced and non-reproducible peaks. By utilizing a

Figure 7. Plot of channel numbers for various inverse-square current settings

needle valve on the gas-flow system situated upstream from the detector and allowing several minutes for the pressure to stabilize before taking data, the reproducibility of the peaks was regained. Apparently, the prior use of a needle valve downstream from the detector was not as effective in stabilizing the gas pressure.

A NaI(Tl) crystal is used to monitor activity inside the spectrometer. The crystal is shielded from electrons, allowing a measure of the gamma counting rate. The crystal is connected to an external photomultiplier tube by a 45.7-cm light pipe. This monitor is used mainly to aid in tuning the separator and observing source strength variations during a scan.

In obtaining gamma-ray counts for analysis, a Ge(Li) detector is used with the system. Either a 6-cm³ detector is placed on top of the spectrometer, or a 60-cm³ detector is located at an equatorial port. For this study, a 60-cm³ Ge(Li) detector was located at a median-plane port to allow simultaneous beta-gamma singles measurements to be taken. The Ge(Li) output is routed through a 1024-channel analyzer and an Address Identifier. The Address Identifier allows the digital setting of three windows within the gamma spectrum in the analyzer. The center window provides the gamma-ray peak counts which are directed to one scaler. The outer two windows provide gamma-ray background counts to another

scaler. A timer is used in connection with a gating signal from the analyzer to provide dead-time corrections to the gamma-ray counts. In the data analysis, the gamma background counts are subtracted from the peak counts. The background counts are multiplied by a normalization factor if the background window width is unequal to the peak window width. The result is then divided by the count time in minutes corrected for the amount of analyzer livetime in the counting period. This gives the area of the gamma-ray peak only, for the same time interval used to count conversion electrons.

There are two other timers associated with the system. One timer has a crystal-controlled time base and measures the count time. The other timer, known as the Time-of-Day, is started at the beginning of the experiment and measures the elapsed time. This is primarily used to provide reference times from which to correct for decay of sources.

4. Beam collection system

For the purposes of simplicity, the Moving Tape Collector (MTC), the Daughter Analysis Control (DAC), and the Readout Interface (RI) systems are combined under the beam collection function of the spectrometer system. The RI coordinates the PDFS with the DAC, which controls the MTC. The DAC provides timing for the functions of beam collection, delay, data accumulation, and tape movement. The RI also controls the method of data output. Gating signals are sent

through the PDFS to allow data to be accumulated when the tape is stationary and the DAC has positioned the desired sources. The complete functioning of these systems can be found in refs. 5 and 11.

The ion beam is deposited on the aluminum side of the aluminized Mylar tape of the MTC. The MTC is a device to allow isobaric separation of the activities provided by the TRISTAN isotope separator. By collecting data at the beam deposition point, the parent activity can be studied. By allowing the ion beam to be deposited on the back side of the MTC probe away from the spectrometer source point, and delaying an amount of time appropriate for the isotope half-life before moving to the accumulation point, the daughter or granddaughter activity can be strongly enhanced in the accumulated data over the parent activity. Since only equilibrium sources were used for this study, the MTC isobaric separation capability was not employed. Therefore, further details of the MTC operation are left to ref. 5. The use of equilibrium sources proved to be sufficient to obtain data as the spectrometer resolution allowed nearly complete separation of the 93.6-keV L-conversion line in the ^{91}Rb decay from the 108.8-keV K-conversion line in the ^{91}Kr decay. Since the overlap of the areas of the peaks was not statistically significant, it was not necessary to enhance the individual isotopes in the sources. Therefore, the equilibrium-source

measurements were easier as no tape movements needed to be made.

For the equilibrium sources used in this study, the DAC was only used to hold the system in the simultaneous collect and accumulate modes to allow beam to be continuously deposited and data to be accumulated for an equilibrium ^{91}Kr , ^{91}Rb source. The RI was then held in the mode where the gating signals allowed total control of the data accumulation and readout to be handled by the PDFS. In fact, in one case, the DAC was by-passed with its input signals to the RI obtained by leaving open or shorting by a terminator plug the appropriate input connectors.

The method of beam stabilization within the spectrometer is noteworthy, however. A stable source position is necessary to maintain spectrometer resolution and calibration. Shifting of the beam position can be caused by variations in the switch magnet field and the spectrometer field. The beam position has been observed to vary 3 mm for a 48,000-channel change of the spectrometer field (11). The beam position also shifts in following the stabilization changes in the collector box. Without stabilization, a 3-mm source shift at channel 48,000 would decrease the resolution from 0.25% to approximately 0.6%. Stabilization is obviously necessary for high-resolution work.

The stabilization method is similar to the use of the pins in the collector box but uses the aluminized Mylar tape directly. Use of a pin system would not work as the pins would act as secondary sources of radioactivity after they became coated by the beam. Therefore, it was decided to use the tape itself by turning it into a two-conductor system. This tape is 12.7 mm wide by 0.0254 mm thick. A 0.0089-mm thick layer of aluminum is bonded to one side of the tape. The aluminum layer provides electrical continuity and better retention of the ions. Besides the use of the tape for stabilization, the electrical continuity allows built-up charge to dissipate before the resolution is degraded by the extra acceleration given to the electrons.

A groove, 0.01 mm deep by 0.3 mm wide, was ground through the center of the aluminum layer for the length of the tape. The two aluminized sides are, effectively, electrically isolated conductors which can act as stabilizer pins. Current from each side of the tape is differentially amplified and directed to a stabilizer which applies a correction voltage to the switch magnet power supply to guide the beam back to the center of the tape, equalizing the current on each side.

IV. METHOD OF ANALYSIS

A. Introduction

Using the definition of an internal conversion coefficient mentioned earlier, the easiest way to determine the ICC of a transition is to measure simultaneously the intensities of the gamma ray and of the internal conversion electrons associated with that gamma ray. Due to the different binding energies of the atomic orbits, the electron peaks for a given transition will be separated in the spectrometer momentum spectrum. Therefore, peaks may be identified as corresponding to the K-, L-, and M-shells. Measurements, then, will actually yield separate K-, L-, and M-conversion coefficients. A total coefficient can be compounded from these, or the individual coefficients or their ratios may suffice to determine the multipolarity of a transition.

The method of simultaneous beta-gamma singles measurements amounts to determining the area of the gamma-ray peak as seen in the multi-channel analyzer, and the area of the conversion electron peak as it is scanned by the spectrometer. Then corrections are made for the efficiency of the Ge(Li) detector, the gamma-ray attenuation by the plexiglas window of the spectrometer, and the geometry of the spectrometer. The correction for the geometry of the spectrometer is most easily done by using data taken under identical condi-

tions for another, well-known transition. The constant geometry factor of the spectrometer can then be eliminated by using the ratio of the unknown to the known ICC.

This method of simultaneous beta-gamma singles measurements, known as the Normalized conversion Peak-to-Gamma peak (NPG) method, was used as exhibited in the formula

$$\alpha_K = \alpha_{K'} \frac{(A_{e'} / A_{\gamma'}) (\epsilon) (ea'x)}{(A_e / A_{\gamma}) (\epsilon') (eax)} .$$

Here, $\alpha_{K'}$ is the known ICC, $A_{e'}$ and A_e are the electron peak areas of the known and unknown transitions respectively, $A_{\gamma'}$ and A_{γ} are the gamma peak areas of the known and unknown transitions respectively, ϵ and ϵ' are the Ge(Li) detector relative photopeak efficiencies at the respective gamma-ray energies, and $ea'x$ and eax are the corrections for gamma-ray absorption losses in the one-half inch plexiglas window of the spectrometer at the gamma-ray energies involved. This last correction involved the use of an "average plexiglas molecule" as $C_5H_6O_2$ (12) and tables of gamma-ray attenuation coefficients (13). The energy-dependent attenuation coefficients are shown in Table 1.

The method of determining the gamma peak areas was mentioned under the description of the Address Identifier of the 1024-channel analyzer on page 22. The electron peak area is determined as follows: After multiplication by a normal-

Table 1. Plexiglas attenuation coefficients

Gamma Energy (MeV)	a_C^1 (cm ² /g)	a_H^1 (cm ² /g)	a_O^1 (cm ² /g)	a_T^2 (cm ² /g)	a_t^3 (1/cm)
.01	2.27	.385	5.72	3.28	3.90
.015	.782	.376	1.78	1.08	1.29
.02	.432	.369	.843	.562	.669
.03	.254	.357	.373	.300	.357
.04	.207	.346	.257	.232	.276
.05	.187	.335	.212	.204	.243
.06	.175	.326	.190	.189	.225
.08	.161	.308	.167	.172	.205
.1	.151	.294	.155	.161	.192
.15	.135	.265	.136	.143	.170
.2	.123	.243	.123	.130	.155
.3	.107	.211	.107	.113	.134
.4	.0953	.189	.0956	.101	.120
.5	.0867	.173	.0873	.0922	.110
.6	.0802	.159	.0805	.0851	.101
.8	.0707	.140	.0708	.0750	.0892
1.0	.0637	.126	.0636	.0678	.0807
1.5	.0516	.103	.0516	.0547	.0651
2.	.0443	.0872	.0444	.0469	.0558
3.	.0355	.0693	.0359	.0376	.0447
4.	.0305	.0581	.0310	.0324	.0386
5.	.0271	.0505	.0278	.0288	.0343

¹Attenuation coefficients taken from Storm and Israel (13).

²A molecularly-weighted average based on $(^{12}\text{C})_5 (^{1}\text{H})_6 (^{16}\text{O})_2$.

³Based on an average plexiglas density of 1.19 g/cm³.

ization factor, the electron counts in the background scaler are subtracted from the foreground counts. These counts are then divided by the count time in minutes and normalized to the source strength which is given by the gamma peak area obtained during the same counting time. The resulting electron

counts are summed numerically over the channel number range that spans the conversion peak. The peak area is then obtained by subtracting the underlying beta continuum as represented by a straight-line fit to the continuum on both sides of the peak.

The relative photopeak efficiencies are determined from a correction curve that is made for each particular detector. The curve is made by measuring the gamma-ray peak areas of many standard sources over a wide energy interval and comparing it to the intensities reported in the literature. At present the determination of the efficiency corrections is believed accurate to 5%.

In determining the error in the ICC, the errors in all factors in the above equation are compounded by standard statistical error propagation. As stated before, the relative photopeak efficiency corrections have a relative error of about 5%, while the error in the gamma-ray absorption correction ratio is about 2%. The relative error in the conversion line areas, which are calculated in the program that determines these areas, is usually less than 1%. If several scans of the conversion line were obtained, the root-mean-square error was used rather than the generally smaller statistical error in the average conversion line area.

B. Source Preparation

For this study three separate equilibrium sources of mass 91 were collected. In the first two cases the sources were collected on the tape from the MTC while it was held stationary. For the last source an external source holder containing a 7-cm length of the "split" tape was used to collect the source. To be certain that the sources were definitely in equilibrium as far as the ^{91}Kr and ^{91}Rb activities were concerned, it was sufficient to delay data accumulation for several minutes after beginning beam deposition on the tape. The half-lives of ^{91}Kr and ^{91}Rb are about 9 and 60 seconds, respectively (7). The mass 91 isotopes and the levels and transitions involved in this study are shown in figure 8.

For the first two mass 91 sources, a source of ^{85}mKr was collected subsequent to obtaining the data on mass 91. This allowed the use of the thoroughly-studied 151-keV transition in ^{85}Rb to provide a known K-conversion coefficient for normalization of the data (14). For the third source collected, the 556-keV transition in ^{91}mY was used as the known, normalization ICC (15). The use of ^{91}mY as the normalization transition in the last source had the advantage that it existed within the same source deposition from which the ^{91}Kr and ^{91}Rb data were collected. This eliminated any possibility of

Figure 8. Mass 91 isotopes and levels in this study

the calibration source being deposited in a slightly different position or with a different shape due to the focus or stabilization, with possible attendant effects on the resolution or transmission of the spectrometer. Such effects, as will be discussed more fully later, can invalidate the assumption that the geometry factor is the same for different depositions.

During the collection of the second source, problems were encountered in electron spectra which were collected. The conversion peak shapes persistently exhibited unexpected "shoulders" mid-way up on the high-energy sides of the peaks. Attempts to remove these shoulders by increasing transmission with corresponding loss of resolution failed. The separator was also running unevenly with unusually large pressure fluctuations, which caused variations of source activity of factors of two. Therefore, data from this source were not used in the results, although a preliminary examination of some of the data gave results not greatly inconsistent with that from the other two sources. The results, which will be discussed below, are shown in Table 2.

C. Measurements and Analysis

From the first source, scans were made of the 93.6-keV K- and L-conversion lines in ^{91}Sr as well as the 108.8-keV K-conversion line in ^{91}Rb . The 108.8-keV K-conversion line was not resolved from the weak 93.6-keV M-conversion line as can

Figure 9. Internal conversion lines of 93.6-keV and 108.8-keV transitions

be seen in figure 9. Since the 93.6-keV L- and 108.8-keV K-conversion lines were resolved, it was possible to determine a K/L ratio for the 93.6-keV transition. The K/L ratio was 5.95 ± 0.24 , which indicates virtually pure E2 multipolarity since the theoretical E2 value is 5.99. The theoretical K/L ratios for E1, M1, M2, and E3 transitions are 9.01, 8.78, 6.83, and 2.65, respectively. Another quantity of interest was the ratio of the 93.6-keV K-conversion coefficient to the 108.8-keV K-conversion coefficient. This ratio was 10.1 ± 0.48 which is the same as Halbig's ratio of 10.1 ± 0.54 (5). The average of these two results, which will be referred to as the K/K' ratio, is 10.1 ± 0.36 . This ratio is predominantly the ratio of the K-conversion electron intensities. Therefore, this ratio will be independent of any geometry normalization. As will be noted later, the ratio value is very close to the theoretical value for a ratio of an E2, 93.6-keV transition to an M1, 108.8-keV transition. The 93.6-keV K-conversion coefficient from the results of the first source was computed to be 2.665 ± 0.115 , which indicates a multipolarity of M2 with an E3 mixing of about 7%. In the calculation of the 93.6-keV K-conversion coefficient, a source of ^{85}mKr was used as a normalization source. This coefficient value was at variance with the results of the K/L and K/K' calculations, which did not involve any normalization source.

Table 2. Results of conversion coefficients
in the decay of ^{91}Kr

Parent Nucleus	IC Transi- tion	Calc. ICC	Theoretical coefficients ¹				
			E1	M1	E2	M2	E3
^{91}Rb	93.6K	1.1922 ± 0.063	0.109	0.172	1.09	1.85	8.89
^{91}Rb	93.6L	$0.2002^{2,3} \pm 0.013$	0.0121	0.0196	0.182	0.27	3.36
^{91}Rb	93.6K/L	5.953 ± 0.24	9.01	8.78	5.99	6.83	2.65
^{91}Kr	108.8K	0.1083 ± 0.007	0.0661	0.101	0.607	0.775	4.95

¹Theoretical internal conversion coefficients taken from Hager and Seltzer (2).

²Calculated from data taken from third source.

³Calculated from data taken from first source.

The K/L and K/K' results, which are internally consistent and involve no separate normalization source, tend to support the E2 nature of the 93.6-keV transition, as had the earlier studies by Mason and Johns (3), Malmskog and MacDonald (4), and Achterburg et al. (7). The shell model predicts that a nucleus with three $d_{5/2}$ neutrons outside a closed shell of $N = 50$ and a closed proton sub-shell of $Z = 38$, will have the lowest excited state as $3/2^+$. The ground state is $5/2^+$. This would also imply that the transition to

the ground state should be E2. Since the K-conversion coefficient calculation was at variance with the other results, and involved an external normalization source, the coefficient calculation was considered unreliable as a characterization of the multipolarity.

Using the more reasonable, shell-model assumption of an E2 character for the 93.6-keV transition and correcting for an E2 93.6-keV M-shell contribution to the area of the unresolved 108.8-keV K- and 93.6-keV M-conversion lines, the 93.6-keV K/L ratio allows one to calculate the 108.8-keV K-conversion coefficient as being 0.108 ± 0.007 . This agrees well with an almost pure M1 multipolarity.

Since conversion coefficient measurements involve the ratio of the areas of the conversion electron to gamma-ray peaks for the known and unknown sources, the suspected error could be in the Ge(Li) detector response or the spectrometer and proportional counter system. Measurements were made with both to see if the source of the error could be found and/or minimized. There are four logical possibilities for the source of any systematic errors in determining gamma peak areas. They are: errors in the detector efficiency, scattering within the exit port, variation of response due to magnetic field, or dead-time gating errors in the analyzer. No variations in the gamma-ray count rate of the Ge(Li) detector had ever been observed for widely separated field settings in

the spectrometer. Likewise, the small energy interval involved would rule out detector efficiency variations as large as the factors of two to four noted in the conversion coefficient. The Ge(Li) detector relative photopeak efficiency correction change is about 6% for the energy interval from 93.6 to 151 keV. Finally, it did not seem probable that such a factor could arise from scattering of gamma rays by the iron walls of the spectrometer as they exit through the port and plexiglas window. Measurements of relative gamma intensities taken with sources inside and outside the spectrometer indicated that any possible effects due to scattering by the iron walls were negligible.

To verify the validity of the gamma peak and background counts as they are corrected for deadtime in the analyzer, a ^{137}Xe beam was introduced into the spectrometer. Beam collection was then stopped, and the source was allowed to decay. Windows were set about the intense 454-keV, gamma transition in the decay. The peak counts were corrected by subtracting background and dividing the result by the ratio of the gamma livetime to count time. If the livetime correction is accurate, the corrected count rate in counts per minute should follow the decay rate of the source. The results are shown in figure 10. The line represents the source half-life and is displaced for clarity. For deadtimes less than 30%, the results indicated no error in the deadtime

Figure 10. Livetime-corrected Ge(Li) detector count rate

correction procedure. All of the spectrometer measurements made prior to this deadtime correction test had less than 30% deadtime, thus the error in ICC normalization could not be due to deadtime correction.

Since systematic errors in gamma peak areas were ruled out, it was concluded that the main error must lie with the determination of the conversion electron peak area. Since a proportional counter has virtually 100% efficiency for all electrons passing through the window, errors in counting must be due to the number of electrons arriving at the counter. And this variation is most probably due to the positioning or shape of the source on the tape within the spectrometer.

To test the effect of the source position on the peak areas, a ^{137}Cs source in an adjustable holder was placed in the spectrometer. The source position could be varied in steps of $1/8$ inch across a width of $1/2$ inch, the width of the "split" Mylar tape. Initially, a variation over the tape width produced peak area changes of 5% to 33% of the peak area corresponding to the center position. Then the baffles defining the solid angle on the detector side were maximally opened to see how this would reduce the position dependence. The variations from one side to the other were 10% to 9%. Next, the baffles on the source side were also opened maximally. This gave variations of 15% to 13%. Finally, with both source and detector baffles wide open, the slit on the

proportional counter was widened from 0.050 inch to 0.100 inch. This caused variations of 7% to 6%. Further measurements were taken to adjust the baffles about the openings to provide the most symmetric peaks and uniformity of resolution. The resolutions varied from 0.4% to 0.6% across the tape at this final setting. For comparison, the resolution at the center position was about 0.2% before the baffles were opened wider.

This degradation of the resolution provided peak areas which were relatively insensitive to the change of source position. However, some effect on the areas due to the position of the source remains. The data did not reveal any area effects on the order of a factor of two, which exists between the value of the 93.6-keV K-conversion coefficient and the theoretical value. The reason for the discrepancy thus remains a mystery.

A third source was used to eliminate the inconsistencies in the data on the 93.6-keV transition from the first source. With the solid-angle adjustments indicated, it was anticipated that the 93.6-keV L- and 108.8-keV K-conversion lines would not be resolved. For this reason, the only quantity measured with the third source was the 93.6-keV K-conversion electron peak, as shown in figure 11. The 556-keV M4 transition of ^{91m}Y was used to obtain the 93.6-keV K-conversion coefficient. The use of both a larger solid angle and a nor-

Figure 11. 93.6-keV K-conversion line from third source

malization transition from the mass 91 deposit were considered to be adequate to eliminate the suspected cause of error in the previous conversion coefficient measurements.

Three scans of the 93.6-keV K-conversion line and four scans of the 556-keV K-conversion line of ^{91}mY were used in this measurement. A fourth scan of the 93.6-keV line could not be used because the reactor momentarily shut-down during the data collection. The 93.6-keV K-conversion coefficient was calculated to be 1.192 ± 0.063 . This is slightly above the theoretical value for a pure E2 transition of 1.09, but it is too far from the M2 value of 1.85 to be that.

Concurrently, Glascock (16) has measured the K-conversion coefficients of the 93.6-keV and 108.8-keV transitions by the X-ray Peak-to-Gamma peak (XPG) method at the TRISTAN facility. The XPG method involves the simultaneous measurement of x-ray and gamma-ray intensities. The detector employed for the measurements was a Low Energy Photon Spectrometer (LEPS). Then the ICC upper limit can be found by dividing the x-ray intensity by the gamma-ray intensity and fluorescent yield. For these measurements, the TRISTAN gamma-ray MTC was used to provide ^{91}Kr and ^{91}Rb sources which were approximately 95% enhanced. Then the x-ray areas were corrected for intensities due to the isotope that was being discriminated against as well as ^{90}Kr hydride that was observed, by the use of known fluorescent yields, a known K-

conversion coefficient for the 121-keV transition in ^{90}Kr , an estimated K-conversion coefficient for the non-enhanced A = 91 contaminant, and the observed gamma-ray peak areas with relative photopeak efficiency corrections. The two calculations were then reiterated to obtain internal consistency in the estimation of the non-enhanced isotope's K-conversion coefficient. This method determined the K-conversion coefficients to be 1.012 ± 0.065 and 0.108 ± 0.011 , respectively for the 93.6-keV and 108.8-keV transitions. These values, as shown in Table 3, agree with the character of the transitions as being pure E2 for the 93.6-keV and virtually pure M1 for the 108.8-keV transitions.

The XPG result of 1.012 ± 0.065 for the 93.6-keV K-conversion coefficient is in good agreement with the NPG result of 1.192 ± 0.063 . The weighted average of these two results is 1.105 with a root-mean-square error of 0.088. It should be emphasized that these two results are completely independent since they involve independent measurement techniques. A further check on the consistency of the results of the 93.6-keV K-conversion coefficients from the NPG and XPG measurements can be made. By multiplying the XPG K-conversion coefficient for the 108.8-keV transition by the spectrometer K/K' ratio, another measure of the 93.6-keV K-conversion coefficient is obtained. This method gives an answer of 1.110 ± 0.117 , in excellent agreement with the

Table 3. Internal conversion coefficients and ratios

Internal Conversion Transition	Theoretical Value ¹	Calculated values			
		Halbig (5)	Achterburg et al. (7)	Glascock (16)	This study
93.6K	1.09 ²	4.16 ±0.46	1.050 ±0.100	1.012 ±0.065	1.192 ³ ±0.063
108.8K	0.101 ⁴	0.412 ±0.024	0.067 ±0.012	0.108 ±0.011	0.108 ⁵ ±0.007
93K/108K	10.8	10.1 ±0.5	15.7 ±3.2	9.4 ±1.1	10.1 ⁵ ±0.5

¹Theoretical internal conversion coefficients taken from Haeger and Seltzer (2).

²Assuming pure E2.

³Calculated from data taken from third source.

⁴Assuming pure M1.

⁵Calculated from data taken from first source.

above average value.

In addition, the spectrometer K/K' ratio may be used with the 1.105 ± 0.088 average K-conversion coefficient for the 93.6-keV transition from above to obtain another measure of the 108.8-keV K-conversion coefficient. The K/K' ratio of 10.1 divided into the average 93.6-keV K-conversion coefficient of 1.105 gives 0.110 ± 0.009 for the 108.8-keV K-conversion coefficient, in excellent agreement with $0.108 \pm$

0.011 from the XPG measurement. The average of these two values is 0.109 ± 0.007 , where the error is statistical.

V. SUMMARY AND CONCLUSIONS

The magnetic beta-ray spectrometer and its associated equipment have been proven a convenient and precise system for the measurement of internal conversion coefficients associated with nuclear transitions. This precision is essential to provide the discrimination necessary in assigning multipolarities to transitions closely-spaced in energy. The reason for the variation in peak areas when using a separate calibration source remains to be identified, however. Until the variation problem is solved, it may be necessary to limit ICC measurements only to transitions within a given source collection.

In the decay of ^{91}Kr , the K-conversion coefficient of the 108.8-keV transition was determined to be 0.109 ± 0.007 . This establishes the transition to be almost pure M1, in contradiction to the E1 result of Achterburg et al. (7).

In the decay of ^{91}Rb , the K-conversion coefficient of the 93.6-keV transition was deduced to be 1.10 ± 0.09 . Furthermore, the K/L ratio was determined to be 5.95 ± 0.24 . Together, these results establish the transition to be pure E2, in contradiction to the results of Halbig (5). It is believed that about 50% of the error in Halbig's result may be due to the use of the wrong relative photopeak efficiency correction for the Ge(Li) detector employed. Presumably, the

remaining error was due to the beam focus or source positioning on the tape, as noted in this study.

The ICC results obtained in this study imply that there are no parity-changing transitions between the ground and first excited states of either ^{91}Rb or ^{91}Sr . As mentioned previously, the ground state of ^{91}Rb should be predominantly a $f_{5/2}$ proton hole. The first opposite parity state would consist of a $g_{9/2}$ particle at relatively high energy, approximately 2 MeV. These considerations led Achterburg et al. (7) to consider a stable deformation to explain the existence of a parity-changing transition between the lowest excited-state and the ground state, although ^{91}Rb is only one proton from a closed sub-shell of 38 and just four neutrons past a closed shell of 50, hardly a nucleus for which low-energy stable deformations would be expected. The results of the present study require no such unlikely assumption.

In the case of ^{91}Sr , Halbig (5) has noted that the ground state of $5/2^+$ is explained by the closed proton sub-shell and three $d_{5/2}$ neutrons. Again no parity-changing transitions would be expected at such a low-energy level. It may be noted that Talmi and Unna (17) have shown that M1 transitions among identical particle configurations are strongly hindered. This is a further argument for a pure E2 transition. They also have shown that the lowest levels should be $3/2^+$, and $9/2^+$ at a higher energy.

The results of this study eliminate the need for any elaborate and unusual explanations which modify the accepted shell model that has been observed to work very well in the region near closed particle sub-shells.

VI. LITERATURE CITED

1. S. A. Moszkowski, "Theory of multipole radiation", in Alpha-, Beta-, and Gamma-Ray Spectroscopy, vol. 2, edited by K. Siegbahn (North-Holland, Amsterdam, 1965), p. 864.
2. R. S. Hager and E. C. Seltzer, "Internal conversion tables, part I: K-, L-, M-shell conversion coefficients for $Z = 30$ to $Z = 103$ ", Nucl. Data A4, 41 (1968).
3. J. F. Mason and M. W. Johns, "Level structures of ^{91}Rb and ^{91}Sr as populated in beta decay", Can. J. Phys. 48, 2895 (1970).
4. S. G. Malmskog and J. MacDonald, "The 93.54 keV level in ^{91}Sr ", Nucl. Phys. A142, 263 (1970).
5. J. K. Halbig, "The beta decay of gaseous fission products", Ph.D. thesis, Iowa State University, 1973 (unpublished).
6. D. P. Ames, M. E. Bunker, L. M. Langer, and B. M. Sorenson, "The disintegration of Sr^{91} and $\text{Y}^{91\text{m}}$ ", Phys. Rev. 91, 68 (1953).
7. E. Achterburg, F. C. Iglesias, A. E. Jech, J. A. Moraques, D. Otero, M. L. Perez, A. N. Proto, J. J. Rossi, and W. Scheuer, "Levels of ^{91}Rb and ^{91}Sr fed in the decays of ^{91}Kr and ^{91}Rb ", Phys. Rev. C9, 299 (1974).
8. W. L. Talbert, Jr. and D. Thomas, "Design considerations for a system to investigate short-lived nuclei produced at a reactor", Nucl. Instrum. Methods 38, 306 (1965).
9. W. L. Talbert, Jr. and J. R. McConnell, "Preparation for on-line studies of short-lived nuclei produced by a reactor", Ark. Fys. 38, 99 (1967).
10. A. A. Bartlett, R. A. Ristinen, and R. P. Bird, "A new double focusing beta spectrometer and the empirical optimization of its performance", Nucl. Instrum. Methods 17, 188 (1962).
11. J. K. Halbig, F. K. Wohn, and W. L. Talbert, Jr., "A magnetic spectrometer system for on-line studies of beta-rays and internal conversion electrons of short-lived activities", Rev. Sci. Instrum. 45, 789 (1974).

12. J. F. Wright, private communication. 1974.
13. E. Storm and H. I. Israel, "Photon cross sections from 1 keV to 100 MeV for elements $Z = 1$ to $Z = 100$ ", Nucl. Data A7, 565 (1970).
14. F. K. Wohn, W. L. Talbert, Jr., and J. K. Halbig, "The decay of ^{85m}Kr ", Nucl. Phys. A152, 561 (1970).
15. J. K. Halbig, F. K. Wohn, W. L. Talbert, Jr., J. J. Eitter, and J. R. McConnell, "The beta decay of ^{91}Sr ", Nucl. Phys. A203, 532 (1973).
16. M. D. Glascock, private communication. 1974.
17. I. Talmi and I. Unna, "Theoretical interpretation of energy levels in light nuclei", Ann. Rev. of Nucl. Sci. 10, 353 (1960).

VII. ACKNOWLEDGMENTS

This author wishes to express his deep appreciation to the many people who have provided assistance and encouragement during this study:

Dr. Fred K. Wohn, who served as thesis advisor and guided this project to completion. He has assisted immeasurably by suggesting the subject of this study and providing interpretations of the results. His patience and steadfastness with this tyro will be long appreciated.

Dr. Willard L. Talbert, Jr., who guided me into nuclear physics and was responsible for the TRISTAN system which made this study possible.

John R. McConnell, who was the real "hands" and "heart" of TRISTAN.

Dr. W. C. Schick, Mike Glascock, and the rest of the members of Group VII for their support.

D. Lekwa, H. Skank, J. Homer, and G. Sledge, who have kept the spectrometer system operating so experiments could be done.

My wife, Susan, who has persevered above and beyond the call of duty.