GAMMA-RAY DECAY SCHEMES FOR ^{91}Kr AND ^{91}Rb

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Ph.D. Thesis Submitted to Iowa State University

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Date Transmitted: May 1975

PREPARED FOR THE U.S. ENERGY RESEARCH AND DEVELOPMENT
ADMINISTRATION UNDER CONTRACT NO. W-7405-eng-82

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Gamma-ray decay schemes for ^{91}Kr and ^{91}Rb ¹

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A study of the resultant gamma-ray de-excitations following the beta decays of ^{91}Kr and ^{91}Rb using the TRISTAN on-line isotope-separator system is reported. Measurements of gamma-ray singles and gamma-gamma coincidences were performed with Ge(Li) detectors. For the decay of ^{91}Kr , 218 of 220 observed gamma-ray transitions have been assigned to a level scheme for ^{91}Rb with 60 excited states. For the decay of ^{91}Rb , 109 of 125 observed gamma-ray transitions have been assigned to a level scheme for ^{91}Sr with 37 excited states. Internal-conversion coefficients and level half-lives were measured for transitions from the first-excited states in both nuclei. Beta branchings were determined from equilibrium measurements and transition-intensity balances. Spin and parity assignments have been made using gamma-ray transition probabilities, internal-conversion coefficients, and deduced $\log ft$ values. Interpretation of some of the energy levels is made on the basis of the shell model and nuclear systematics.

¹USERDA Report IS-T-672. This work was performed under contract W-7405-eng-82 with the U. S. Energy and Research Development Administration.

I. INTRODUCTION

The aim of nuclear studies is to infer the nature of the nucleon-nucleon interaction from the observed properties of nuclei and from nuclear reaction properties. The information which can be obtained from orderly investigations into the dependences of nuclear properties will lead to a better understanding of the nuclear phenomenon than that we have today. Moreover, information about half-lives, decay radiations, neutron-separation energies, and decay energies, is valuable for those who work in astrophysics, health physics, and reactor physics.

Several complications hinder our quest for complete determination of the character of the internucleon interaction. The simplest system to examine, obviously, is the system consisting of only two nucleons. Unfortunately, the only bound two-nucleon system is the deuteron which has a single bound state. Further complication to the picture arises in the complex nature of the interaction which is attractive at separation distances of 2 fm, becomes repulsive when these distances are 0.4 fm, and requires inclusion of non-central (tensor) forces. In view of these difficulties, detailed studies of nuclear structure are considered essential to develop a body of information from which certain properties of the nucleus can be deduced, usually from some model-dependent basis.

A. Short-lived Nuclides

Only about one-third of the 1600 nuclei shown on a chart of the nuclides exist as stable isotopes. Calculations by Seeger and Howard (1) suggest the existence of more than 8000 nuclides between the lines of particle stability, most of which are expected to have half-lives shorter than 10^2 seconds. Extensive information of nuclides in general exists only near the valley of beta stability. The absence of knowledge for the large number of remaining nuclei restricts studies of nuclear systematics.

These short-lived nuclides do not appear in nature because of their rapid decay to stable daughters. Meaningful spectroscopic studies of such nuclides are possible only if a continuous manner of production is available. There are three main ways of producing short-lived nuclei far off the stability line--namely spallation, heavy-ion reactions, and fission (2). Spallation with high-energy protons and heavy-ion reactions produce very neutron-deficient nuclei. The fission of heavy nuclei produces neutron-rich fragments. This last method of production was used to produce the short-lived nuclei for this study.

B. Fission

Fission is the process in which a heavy nucleus splits into two fragments with a considerable release of energy and

the emission of neutrons, gamma rays, beta rays, and neutrinos either at the instant of fission or sometime later as the fragments decay. Because the binding energy per nucleon is a decreasing function of A , for A greater than 50, a more stable configuration results when a heavy nucleus splits into two lighter nuclei. On this basis, it would appear that all heavy nuclei would undergo spontaneous fission. However, many heavy nuclei are found to be either stable or very long-lived and only rarely undergo spontaneous fission.

In a simple model of fission, the fissioning nucleus begins as a sphere, becomes deformed into a sequence of dumbbell-shaped intermediate states, and completes the process by separating into two distinct fragments. In order to deform the nucleus into a dumbbell configuration, an external source of energy (known as the activation energy) must be supplied. The potential energy of this system increases as the fissioning nucleus transforms through these intermediate states. This is due to the fact that at short range the nuclear force is more attractive than the Coulomb force is repulsive. This increase in potential energy continues until the lobes of the dumbbell separate. From this point on, the potential energy of the system decreases since the Coulomb repulsive energy between the two fragments decreases as the fragments separate.

The absorption of high-energy gamma rays and neutron absorption are two methods of supplying the energy for fission. The absorption of a neutron gives the compound nucleus an excitation energy equal to the neutron kinetic energy plus the binding energy from adding this neutron to the system. When a neutron with zero kinetic energy is added to ^{235}U , the compound nucleus ^{236}U is given an additional energy of 6.4 MeV. This provides the system with more than the required threshold energy of 5.3 MeV, and fission then proceeds immediately.

The masses of the nuclear fragments which result from fission are dependent on the mass of the parent nucleus and the energy input by the incident particle. However, the distribution of the fragment masses is generally asymmetric primarily due to shell effects for the fragments. For example, the thermal-neutron induced fission of ^{235}U has a fragment distribution which peaks near $A = 95$ and $A = 139$ and decreases rapidly on both sides of each mass peak as shown in Figure 1. The fragments are typically very neutron rich which makes them susceptible to radioactive decay by beta emission.

C. Beta Decay

Beta decay is the process by which an electron is emitted directly from the nucleus, increasing the atomic number by unity but not changing the mass number.

Figure 1. Fission yield of ^{235}U as a function of mass number and proton number, with mass yield and element yield profiles

Conservation of energy and angular momentum require that a neutrino, in addition to the electron, be emitted in beta decay. The maximum kinetic energy available for the emitted electron is known as the Q-value (Q_β), which is the difference in ground-state rest mass energies between the parent and daughter nuclei. Figure 2 shows pictorially the Q-values for beta decay in the $A = 91$ decay chain beginning with ^{91}Kr .

Each nuclide will decay over a characteristic period of time. The half-life represents the period of time during which one-half of the original nuclei decay.

Very often the beta decay will leave the daughter nucleus in an excited state. The electron and neutrino kinetic energies sum to the difference of energies of the ground state of the parent nucleus and the excited state of the daughter nucleus. When the daughter nucleus is populated in a certain state by virtue of a beta emission, the fraction of beta decays to that state is known as the beta branch. Beta decay to the states of the daughter will be favored or hindered dependent on the selection rules for changes in angular momentum and parity from the parent nucleus to the daughter nuclear state. A quantitative measure which is related to the likelihood of beta emission from the parent to the daughter is expressed by the comparative lifetime, or logft value, for the beta branch in question.

Figure 2. $A=91$ beta-decay chain studied in this work

D. Gamma-ray Transitions and Internal Conversion

The excited states in a daughter nucleus are usually quite short-lived (typically 10^{-15} seconds). The nucleus will usually undergo de-excitation to the ground state or other excited states via one or more gamma rays. The probability of a gamma-ray transition from initial state to final state is dependent on the angular momenta and parities of the connected states (determined by the initial and final configurations of the nucleons).

Because a nucleus is actually an extended charge distribution in which the orbital and spin motions of the nucleons generate currents, the charge distribution can be expanded into electric and magnetic moments. Electromagnetic transitions with photon emission are triggered by changes in these moments induced by a change in nucleon configuration. Gamma-ray transitions between states may be of either pure or mixed multipole type. The possible multipolarities for transitions between states J_i and J_f are given by:

$$|J_i - J_f| \leq L \leq J_i + J_f$$

In general, the transition probability decreases very rapidly with increasing multipolarity. The rules regarding parities of initial and final states for electric and magnetic multipole transitions, respectively, are:

$$\pi_i \pi_f = (-1)^L$$

and

$$\pi_i \pi_f = (-1)^{L+1}$$

If a state is quite long-lived (typically 10^{-9} seconds or greater), the state is called an isomeric state. Large differences in angular momentum and small energy differences with respect to the ground state cause excited states to become long-lived. Ratios of experimental half-lives to the Weisskopf estimates, if greater than one, are known as hindrance factors. Figure 3 shows for $Z = 55$ the Weisskopf half-life estimates not corrected for internal conversion.

Internal conversion is a de-excitation process in competition with gamma-ray emission. During internal conversion the energy difference between initial state and final state is transferred to an atomic electron, which is ejected with a kinetic energy:

$$T = E_i - E_f - E_B$$

where E_B is the binding energy of the electron in the atomic shell from which it has been displaced.

The internal-conversion coefficient (ICC) for a transition is the ratio of the probability for ejecting electrons to the probability for gamma-ray emission. The ICC depends sensitively on the type and multipolarity of the accompanying gamma-ray transition. Internal conversion is an increasing function of L and Z and a decreasing function of the difference between initial and final state energies.

Figure 3. Weisskopf estimates for the half-lives of E1, M1, E2 and M2 transitions

The ICC often gives an accurate indication of the multipolarity of a transition.

A secondary process always accompanies internal conversion because the atom has been left in an excited state with energy E_B . Either X rays are emitted, or Auger electrons are released from the outer atomic shells to remove the excitation energy. The number of X rays or Auger electrons emitted relative to the number of gamma rays emitted gives a measure of the ICC.

E. Previous Studies of ^{91}Kr and ^{91}Rb

The short-lived nuclide ^{91}Kr is produced with an absolute cumulative yield of 3.46% (3) from the thermal-neutron induced fission of ^{235}U . Both ^{91}Kr and its short-lived daughter ^{91}Rb decay through beta-emission and populate the levels of ^{91}Rb and ^{91}Sr . The latter are of particular interest due to their nearness to nuclei with semi-closed shell $Z = 38$ and closed shell $N = 50$.

Kofoed-Hansen and Nielsen (4) at Copenhagen were the first to identify the decays of ^{91}Kr and ^{91}Rb in 1951. They reported the parent and daughter nuclei to have half-lives of 10 sec and 100 sec, respectively. Other early investigations of the half-lives were reported by Wahl, *et al.* (5), Wahlgren and Meinke (6) and Amarel, *et al.* (7). A more recent measurement made by Carlson, *et al.* (8) determined

the half-lives to be 8.57 ± 0.04 sec and 58.2 ± 0.2 sec for the decays of ^{91}Kr and ^{91}Rb , respectively. The Q -values for the decays of ^{91}Kr and ^{91}Rb were reported by Clifford, et al. (9) to be 6.12 ± 0.07 MeV and 5.68 ± 0.04 MeV, respectively.

Borg, et al. (10) and Amiel, et al. (11) reported energies for the prominent gamma rays observed in the decay of ^{91}Kr while studying on-line techniques to achieve isobaric enhancement. The first decay scheme for ^{91}Kr was proposed by Eidens, et al. (12) which included three levels with two connecting transitions and approximately 20% of the ^{91}Kr beta decays going directly to the ground state of ^{91}Rb . Mason and Johns (13) proposed a scheme with four excited states involving six transitions. A recent study was reported by Achterberg, et al. (14) in 1974 which reported 31 levels and 94 connecting transitions. Achterberg, et al. also proposed a parity-changing transition in ^{91}Rb from the first-excited state to the ground state. This transition could not be explained on the basis of the spherical shell model; thus, they suggested the existence of a stable deformation for some excited levels in ^{91}Rb . This suggestion is open to serious question, according to the systematics of nuclear structure for nearby nuclei and subsequent measurements reported here.

Three levels of ^{91}Sr populated by the decay of ^{91}Rb were reported by Malmskog and McDonald (15) in 1969 with three connecting transitions. In addition, they reported the existence of a largely E2 isomeric transition from the first-excited state in ^{91}Sr which has been confirmed by Mason, et al. (16). Mason and Johns (13) presented a level scheme with 18 levels accounting for 28 transitions. The most recent study of ^{91}Rb decay was by Achterberg, et al. (14) who reported 39 transitions within a scheme of 16 levels.

II. EXPERIMENTAL TECHNIQUES

A. Sample Preparation

The TRISTAN on-line isotope separator located at the Ames Laboratory Research Reactor and described in the literature (17, 18, 19, 20) is ideal for studying the radioactive decays of the fission products of ^{235}U and their daughters. The layout of TRISTAN is shown in Figure 4. An aluminum container with about 10 g of fully-enriched uranyl stearate is placed in an external beam of the reactor with a flux of 3×10^9 neutrons/cm²/sec. At present, only the inert gas fission products are emanated in copious quantity and reach the ion source which is located 1.6 m from the fission product source.

After they have been ionized and extracted from the ion source, the inert gas ions are focused and accelerated through 50 kV. A 90° sector magnet with a mean radius of 160 cm isotopically separates the ion beam which is deposited on aluminized Mylar tape in a moving tape collector (MTC). The MTC enhances, as explained in detail by Norman, et al. (21), either the parent or a daughter activity. Compared to equilibrium activity, the enhancement factors were 20 for the decay of ^{91}Kr and 100 for the decay of ^{91}Rb , making possible an unambiguous identification of the gamma-ray transitions observed. Slight amounts of contamination were usually seen from the $A = 90$ hydrides, ^{60}Co , and ^{41}Ar .

Figure 4. Schematic layout of the TRISTAN isotope separator facility

B. Detection Methods

Four Ge(Li) detectors and a plastic scintillator were used in gathering spectra for this study. Resolutions, efficiencies, and peak-to-Compton ratios for the Ge(Li) detectors are given in Table 1. Efficiencies are relative to that of a 7.6-cm by 7.6-cm NaI(Tl) crystal and resolutions were obtained from counting ^{57}Co and ^{60}Co sources. Beta radiation is shielded from the large volume detectors by 0.63-cm thick Lucite absorbers and from the planar low-energy photon spectrometers (LEPS) by thin Be windows.

Table 1. Detectors used in experiments

Detector geometry	Active volume (cm)	Resolution @ energy (keV)	Efficiency	Peak/Compton for 1332-keV gamma ray
true coaxial	57.3	2.7 @ 1332	11.8%	34/1
true coaxial	58.2	2.7 @ 1332	9.0%	28/1
planar	1.0	0.750 @ 122	N/A	N/A
planar	1.0	0.450 @ 122	N/A	N/A

The plastic scintillator was a 25-mm-thick by 44-mm-diameter cylinder of NE102 plastic mounted on an Amperex PM2106 12-stage photomultiplier tube operated at 2000 V. Pulse risetime of the detector was less than 5 nsec.

C. Data Acquisition

1. Gamma-ray singles

A block diagram of the equipment used in collection of singles data is shown in Figure 5. The Ge(Li) detector was mounted at the appropriate port of the MTC to accumulate the activity to be studied. The signal from the Ortec Model 120 Preamplifier was fed to a Tennelec Model TC203BLR Linear Amplifier. The main amplifier output was connected to a 8192-channel Geoscience Nuclear Model 8050 Analog-to-Digital Converter (ADC). Resolution and peak shape were optimum when a four-microsecond time constant, baseline restoration, and DC coupling were used. An auxiliary amplifier output was usually connected through a Canberra Model 1430 Single Channel Analyzer to a Hamner Model N-780A Ratemeter.

The ADC processed the data into a 16384-channel modified Technical Measurements Corporation analyzer with a capacity of $10^5 - 1$ counts per channel. The 8192-channel spectrum was transferred to magnetic tape whenever the number of counts in the peak channel approached overflow. The analyzer memory was then erased and another accumulation begun. The resulting spectra were later added together for analysis.

Measurements to determine gamma-ray transition energies and intensities were taken over an energy range sufficient to give a spectrum up to the Q-value of each isotope.

Figure 5. Diagram of singles electronics system

ADC live-time was maintained at approximately 80% during data accumulation to minimize pulse pile-up.

A typical singles measurement consisted of four separate accumulations of data--calibration, calibration with unknown, unknown, and background. Appendix A lists the energies of the calibration sources of ^{56}Co , ^{57}Co , ^{60}Co , ^{133}Ba , ^{137}Cs , ^{182}Ta , ^{192}Ir , and ^{226}Ra used to obtain energy and intensity calibration and system nonlinearity correction.

The presence of a high Compton background beneath the very intense gamma rays near 100 keV caused a large uncertainty in the fitted areas for these gamma rays. A high resolution LEPS was then used in the same configuration as the large Ge(Li) to gather a spectrum from 0 - 550 keV. The intensities of these strong transitions relative to several other low-energy transitions were then determined with much lower uncertainties.

2. X-ray measurements

A LEPS detector was also used to accumulate spectra of the X rays and low-energy gamma rays in each decay. Since both A = 91 decays have only a single intense gamma ray at low energy, it was possible to obtain a measure of the internal-conversion coefficients for these transitions using the X-ray-peak-to-gamma-peak method (XPG) which is discussed in Chapter III, Section C.

3. Gamma-gamma coincidence measurements

Gamma-gamma coincidence measurements were performed with two 60-cm³ detectors separated by 10 to 15 cm in 180° geometry. Constant-fraction timing units were used, with a 40 nsec timing window. The block diagram in Figure 6 shows the setup for performing a coincidence experiment where the buffer tape system of data storage was used.

The following equipment was used in the gamma-gamma coincidence experiments:

Preamps: Ortec Model 120

Timing Filter Amplifiers: Ortec Model 454

Constant-Fraction Timing Discriminators: Ortec Model 453

Time-to-Pulse-Height Converter: Ortec Model 437

Single Channel Analyzer: Canberra Model 1430

Linear Amplifiers: Tennelec Model TC203BLR

Delays: Measured delay cables

ADC's: Geoscience Nuclear Model 8050

The buffer tape system employed a 12-bit, 4096-word memory in which the addresses of every pair of coincidence events from the ADC's were recorded. For this experiment, each pair of events consisted of a channel number corresponding to the energy of the gamma ray registered by detector A, and simultaneously, a channel number corresponding to the energy of the gamma ray registered by detector B. When the buffer memory was filled to its capacity of 2048 coinci-

Figure 6. Diagram of coincidence electronics system

dence events, the data was automatically transferred to a magnetic tape and the memory reset to zero before resuming the accumulation of events. A typical magnetic tape, when filled, held approximately 3.5×10^6 coincidence events with a 4096-by-4096-channel resolution.

To extract the information of interest, the buffer tapes could be played back into the analyzer memory through a format selection system (or later using the computer program BUFFTape). Digital gates were set on the peaks of interest and nearby backgrounds in one of the two coincidence spectra. The playback into the analyzer resulted in a spectrum of the gamma rays seen by the other detector in coincidence with each gated peak and associated background. These gates were then transferred to another magnetic tape for further analysis.

4. Beta-branching measurements

Gamma-ray singles spectra of the decays of ^{91}Kr and ^{91}Rb were accumulated with these activities in equilibrium with the ion beam in order to determine the ground-state beta branchings. The ground-state beta branching and proposed level scheme for each decay were then used to determine the branchings to all excited states. A detailed description of the procedure for calculating the ground-state beta branching from the experimental data is given in Chapter III, Section E.

Accumulation of data began seven minutes after initiating the deposit of the ion beam to permit both the ^{91}Kr and ^{91}Rb decays to reach equilibrium. ADC live times, equilibrium gamma-ray spectra, and times of accumulation were recorded each thirty minutes for two hours. At the end of two hours, the activity deposition was halted and the collected source was allowed to decay. This decay was monitored for several hours (after the short-lived ^{91}Kr and ^{91}Rb activities had decayed away) in order to accumulate gamma-ray spectra of the ^{91}Sr decay. These spectra, with appropriate corrections for the 9.48-h half-life of ^{91}Sr , allowed the determination of the intensities of ^{91}Kr and ^{91}Rb gamma rays relative to ^{91}Sr decays. Since the ground-state beta branching of ^{91}Sr is known (22), the ground-state beta branchings of ^{91}Kr and ^{91}Rb were then deduced from the relative gamma-ray intensities.

5. Delayed-coincidence measurements

A plastic scintillator and a LEPS detector were used to measure the delayed-coincidence time spectra using an arrangement which has been previously described by Morman, et al. (23). The block diagram shown in Figure 7 indicates the use of constant-fraction discriminator timing. The delay between a start pulse (representing formation of a nuclear state) and a stop pulse (representing decay of the state by gamma-ray emission) is registered as a time interval by a

Figure 7. Diagram of level half-life measurement system

time-to-pulse-height converter for which an appropriate time range has been selected. This signal is then sent to one ADC.

Another LEPS detector signal is sent into a linear amplifier which is followed by the other ADC. Long risetime pulses from the LEPS are eliminated in the analysis by a pulse shape analyzer to reduce the tailing effect on the upper side of the timing peak. Time calibration was performed with precision timing pulses generated by a time calibrator. The coincidence event stored by the buffer tape system represents an energy-time pair. The following equipment was used in the gamma-time coincidence experiments:

Preamplifier: Ortec Model 117A

Timing Filter Amplifiers: Ortec Model 454

Constant Fraction Discriminators: Ortec Model 463

Time-to-Pulse-Height Converters: Ortec Model 437

Timing Single Channel Analyzer: Ortec Model 420

Delay Line Amplifier: Ortec Model 460

Pulse Shape Analyzer: Ortec Model 458

Slow Coincidence Unit: Canberra Model 1445

Linear Amplifier: Ortec Model 452

Delay Amplifiers: Mech-Tronics Nuclear Model 506

ADC's: Geoscience Nuclear Model 8050

Time Calibrator: Ortec Model 462

Energy peaks and backgrounds in the energy profiles were gated in the same manner as for gamma-gamma coincidences. The resulting time spectra were then stored on a magnetic tape to be analyzed further.

III. DATA ANALYSIS

Experiments in nuclear spectroscopy generally yield enormous volumes of data. Manual data analysis, in addition to being quite tedious, fails to use the capabilities of Ge(Li) detectors to full advantage. As a result, computer reduction of data in nuclear spectroscopy becomes highly desirable for the unfolding of unresolved multiplets, determining energies, developing complex decay schemes, and handling large volumes of data.

Experimenters at TRISTAN have developed several sophisticated computer codes for analyzing the different types of raw data in a systematic manner. The important programs used during the various phases of this analysis are described in Appendix B.

A. Transition Energies and Intensities

Singles spectra yield transition energies, intensities, and errors which are needed to construct a decay scheme. Peak centroids, heights, areas, and their associated uncertainties were found by fitting the peaks observed in the four separate runs--calibration, calibration plus unknown, unknown, and background. Programs PEAKFIND and SKEWGAUS were used to locate and fit all of the peaks found in each spectrum.

DRUDGE was used to analyze the calibration spectrum, determine the relative detector efficiency, find the system nonlinearity, and furnish information for the single- and double-escape to photopeak ratios. The calibration plus unknown spectrum was then analyzed to determine the energies of the intense unknown peaks using the calibration peaks as an internal calibration. Above 3.45 MeV (the highest energy calibration line available), a bootstrap method was employed using single- and double-escape peaks to determine the corresponding energies of photopeaks, which in turn were used to calibrate neighboring escape peaks and continue the bootstrapping to higher energies.

The energies of the intense unknown peaks were then used within the unknown run to determine energies of the remaining unknown peaks. Any interferences between photopeaks and single-escape, double-escape, or Compton peaks were identified by DRUDGE. Low-intensity peaks which might be due to statistical fluctuations in the background were not retained unless their intensities were at least twice their intensity uncertainties. Peaks in the background spectrum were identified to eliminate possible contaminant peaks in the unknown run from long-lived activities. It was not unusual to identify more than 200 photopeaks as belonging to a particular decay.

B. Coincidence Spectra

Analysis of coincidence spectra was accomplished by plotting the peak gate spectrum and a nearby background gate spectrum. Coincidences were identified by visual inspection, except for multiple placements, in which case, peaks of interest in the gate spectrum were analyzed to find relative peak areas and determine what portion of the intensity went with each placement.

If the number of counts corresponding to a particular transition was greatly enhanced in the peak gate spectrum relative to a nearby background, the transitions were labelled as being definitely coincident. A transition slightly enhanced in the gate relative to the background was labelled as being only possibly coincident. A transition which was found to be more enhanced in the background was considered to be non-coincident.

C. Internal-conversion Coefficients

Internal-conversion coefficients were determined by fitting the low-energy singles spectra with SKEWGAUS. Since virtually all of the observed X-ray intensity was due to the conversion of the 108.8-keV and 93.6-keV transitions in the ^{91}Kr and ^{91}Rb decays, respectively, the corresponding ICC for K-shell electrons could be found by using a method known as the X-ray-peak-to-gamma-peak (XPG) method.

The XPG method requires knowledge of I_K and I_γ , the relative intensities of the K-shell X rays and the associated gamma ray, respectively, and ω_K , the value of the K-shell fluorescence yield (fraction of K vacancies resulting in K-shell X rays) found in Lederer, et al. (24). The expression for calculating the K-shell ICC is:

$$\alpha_K = \frac{I_K}{\omega_K I_\gamma}$$

The total ICC could then be found by referring to the ICC tables of Hager and Seltzer (25).

D. Decay Scheme Construction

The decay schemes were constructed by using program LVLSURCH which required a few known levels as a basis from which to search for new levels. The program searched for all possible new levels by summing unassigned transitions to the known levels.

The possible levels were required to meet certain conditions before they would be added to the list of known levels. A confidence index (CI) was established during the construction of the decay scheme. For a particular level, the CI was given by $CI = N_p + N_d + 2N_c + N_{pc}$. Where N_p and N_d represented the number of transitions populating and depopulating the level, respectively. N_c and N_{pc} were the respective numbers of definite and possible coincidences asso-

ciated with the level. Typically, the minimum condition for accepting a new level into the decay scheme was $CI = 4$. Another requirement was that the sum of intensities into a level be no greater than the sum of intensities out. This last requirement took into account internal conversion when the contribution from that process was not negligible.

E. Beta Branchings and $\log_{10} f_t$ Values

In order to calculate the $\log_{10} f_t$ value for a particular level fed by beta decay, it is necessary to know the percentage of total beta decay feeding that level. Program LEAF initially calculates the relative beta branchings to all excited states with an input ground-state beta branching of zero. This is accomplished by calculating the difference between the sums of gamma-ray and internal-conversion transition intensities into and out of each level of the daughter nucleus.

A convenient method of calculating the ground-state beta branching can be used when the decays of the parent, daughter, grand-daughter, etc., are in equilibrium. In this instance, the number of decays per unit time into and out of all the ground states are equal. If the ground-state beta branch in one of the decays is known, then finding the relative intensities of gamma rays in each decay provides the ground-state beta branching in each of the other decays.

Programs SKEWGAUS and DRUDGE were used to find the gamma-ray intensities in the equilibrium-activity spectra of the decays of ^{91}Kr and ^{91}Rb relative to the gamma-ray intensities in the non-equilibrium spectra of the decay of ^{91}Sr . The ^{91}Sr activity is a fraction of equilibrium ^{91}Sr activity which can be determined from the time behavior of the ^{91}Sr decay. The primary assumptions were:

- 1) Only ^{91}Kr activity is deposited by the mass 91 ion beam. (Chapter II, Section A explains the exclusion of non-gaseous ions.)
- 2) ^{91}Y level scheme as reported by Knight, et al. (26) and the ground-state beta branching from ^{91}Sr as reported by Halbig, et al. (22) are accurate.
- 3) The gamma-ray decay schemes determined for ^{91}Kr and ^{91}Rb are correct.

If $N_{\gamma_{gs}}^1$ and $N_{\gamma_{gs}}^2$ represent the number of transitions from excited states to the ground states of the two nuclides in equilibrium, then the expression

$$\frac{N_{\gamma_{gs}}^1}{N_{\gamma_{gs}}^2} = \frac{100 - \beta_{gs}^1}{100 - \beta_{gs}^2}$$

relates β_{gs}^1 and β_{gs}^2 , the respective percentages of ground-state beta branchings. Both $N_{\gamma_{gs}}^1$ and $N_{\gamma_{gs}}^2$ are calculated from the equilibrium data and either β_{gs}^1 or β_{gs}^2 must be known from some other measurement. Ground-state branchings determined from the equilibrium data are then input to program LEAF which calculates the absolute beta branchings. Program LOGFT deduces the appropriate $\log ft$ values.

F. Spin and Parity Assignments

Spin and parity assignments were made on the basis of the deduced $\log ft$ values, multipolarity assignments for transitions, and overall consistency of gamma transitions.

The rules followed in making spin and parity assignments from deduced $\log ft$ values were suggested by Baman and Gove (27), and are listed below:

$\log ft \leq 5.9$	$\Delta J = 0, 1$	$\Delta \pi = \text{no}$
$\log f_1 t \leq 8.5$	$\Delta J = 0, 1$	$\Delta \pi = \text{yes or no}$
$\log ft \leq 11$	$\Delta J = 0, 1$	$\Delta \pi = \text{yes or no}$
	$\Delta J = 2$	$\Delta \pi = \text{yes}$
$\log ft \leq 12.8$	$\Delta J = 0, 1, 2$	$\Delta \pi = \text{yes or no}$

The rules applied to gamma-ray transitions were:

Parity unchanging: M1, E2, M3, and E4 transitions involve no parity change. E2 and M1 are usually considered to have equal strength. Both E2 and M1 are extremely dominant over M3 and E4 transitions. Most M1 transitions are hindered by a factor of 100, and nearly all M1's lie between a hindrance factor of 10^4 and an enhancement factor of 10. In general, enhancement factors ranging from 10 to 300 are usually found for E2 transitions.

Parity changing: E1, M2, E3, and M4 transitions involve parity change. E1 transitions are dominant over M2 and both are very dominant over E3 and M4. E1 transitions are often hindered by as much as 10^8 , but rarely near closed shell nuclei.

From experimental observation it has been found that electromagnetic decays obey the parity selection rules to a high order of precision.

G. Level Half-life Determination

The observed time spectra were fit with a five-parameter function which uses a non-linear, least-squares method described by Morman, et al. (23). The five parameters were: λ , the decay constant; C , a normalization constant; D and E , the parameters to describe chance coincidences; and G , the residual contribution from prompt transitions. The expression for the fit function was written as:

$$F(t_i) = C \sum_{j=0}^i e^{-\lambda t_j} \cdot P(t_i - t_j) + D \cdot t_i + E + G \cdot P(t_i)$$

Program TIMEFIT5 minimizes χ^2 , which is defined by the expression:

$$\chi^2 = \frac{\sum_i w_i [F(t_i) - y_i]^2}{\sum_i w_i}$$

$F(t_i)$ is from the calculated fit function, $P(t_i)$ is the prompt spectrum (background), y_i is the corresponding data point, and w_i is the statistical weight of the data point. Figure 8 shows a typical delayed-coincidence spectrum in part (a) and a typical prompt-background spectrum in part (b), for the 93.6-keV transition in the ^{91}Sr level scheme.

Figure 8. From the decay of the 93.6-keV level in ^{91}Sr , (a) delayed transition and (b) prompt background spectra

IV. EXPERIMENTAL RESULTS AND DECAY SCHEMES

Most of the aspects of this investigation are summarized in the spectra, tables, and diagrams found in this chapter. Enhanced spectra are shown for each decay with several prominent transitions labelled by energy. Additional peaks due to other isobaric activities or due to contaminant and/or background sources are identified.

Tables listing transition energies, intensities relative to the most intense gamma ray observed, gamma-ray intensities observed per 100 beta decays, and uncertainties as determined by programs DRUDGE and LEAF are presented. These tables also indicate assignments for transitions in the daughter nucleus as determined by LVLSURCH.

Coincidence intensities were used to decide what portion of the transition intensity went with each placement for those transitions which have multiple placements. Each decay has a table listing observed coincidences, if any, for the gated transitions.

Level diagrams are proffered indicating assignments resulting from coincidence data, energy summing, and intensity information. The symbols denoting coincidences have been included according to the following rules: a solid dot indicates one definite coincidence or at least two possible coincidences; an open circle indicates that only one possible coincidence was observed. Transition intensities per

100 decays are listed in parentheses beside the gamma-ray cascades. Dashed levels were identified on the basis of a single coincidence or fewer than three energy sums.

Tables of beta branchings and deduced $\log ft$ values from program LOGFT are given for the levels of the daughter nucleus. Spin and parity assignments for the levels are discussed on the basis of gamma-ray transition probabilities, internal-conversion coefficients, and deduced $\log ft$'s.

Results from other aspects of these decays, i.e., conversion coefficients, ground-state feedings, and level half-lives are presented in other sections of this chapter.

A. The Decay of ^{91}Rb to Levels in ^{91}Sr

The gamma-ray singles spectrum for the decay of ^{91}Rb is shown in Figure 9 and the energies of the 125 gamma rays attributed to this decay with their associated relative intensities are given in Table 2. The resulting energies are in agreement within the quoted errors of other investigators (13, 14). Gamma rays at 1023, 1594, 1823, 2783, 2789, 3147, 3271, 3604, 3643, and 3949 keV with $I_\gamma > 10$ were not previously reported. The peaks at 2331, 2424, 2714, and 3334 keV which had been identified as photopeaks were found to be due entirely to escape peaks. In addition, the multiplets at 1624-1625-1628, 3600-3604, 3639-3644, and 3736-3746 keV have been resolved in this work.

Figure 9. Gamma-ray spectrum from the decay of ^{91}Rb

Table 2. Gamma rays observed in the decay of ^{91}Rb

Energy (keV)	Relative Intensity ¹	Intensity per 100 Decays ²	Assignment (keV)
93.63 $\pm$ 0.02	1000.00 $\pm$ 51.21	31.37	93 --> 0
345.43 $\pm$ 0.03	246.06 $\pm$ 12.24	7.72	439 --> 93
439.15 $\pm$ 0.03	61.60 $\pm$ 3.20	1.93	439 --> 0
509.61 $\pm$ 0.50	5.07 $\pm$ 0.80	0.16	1740 --> 1230 ³
593.23 $\pm$ 0.03	38.16 $\pm$ 2.04	1.20	2657 --> 2064
602.85 $\pm$ 0.03	84.05 $\pm$ 4.33	2.64	1042 --> 439
702.66 $\pm$ 0.25	3.11 $\pm$ 0.45	0.10	
749.73 $\pm$ 0.25	3.28 $\pm$ 0.57	0.10	4793 --> 4043
816.48 $\pm$ 0.47	3.01 $\pm$ 0.67	0.09	
875.02 $\pm$ 0.30	3.20 $\pm$ 0.51	0.10	1917 --> 1042
912.78 $\pm$ 0.39	2.13 $\pm$ 0.72	0.07	
917.59 $\pm$ 0.22	5.45 $\pm$ 0.94	0.17	2657 --> 1740
948.49 $\pm$ 0.05	34.74 $\pm$ 1.87	1.09	1042 --> 93
993.69 $\pm$ 0.13	8.90 $\pm$ 0.80	0.28	4358 --> 3364
1006.29 $\pm$ 0.39	2.76 $\pm$ 0.66	0.09	2236 --> 1230
1023.20 $\pm$ 0.12	13.05 $\pm$ 1.10	0.41	2064 --> 1042
1034.86 $\pm$ 0.59	3.90 $\pm$ 1.62	0.12	3693 --> 2657
1041.99 $\pm$ 0.05	64.98 $\pm$ 3.47	2.04	1042 --> 0
1137.24 $\pm$ 0.05	115.46 $\pm$ 6.04	3.62	1230 --> 93
1149.72 $\pm$ 0.69	2.00 $\pm$ 0.80	0.06	4793 --> 3643
1174.07 $\pm$ 0.53	2.90 $\pm$ 0.76	0.09	3831 --> 2657
1205.56 $\pm$ 0.33	3.42 $\pm$ 0.66	0.11	3364 --> 2159
1230.64 $\pm$ 0.15	8.73 $\pm$ 0.79	0.27	1230 --> 0
1238.65 $\pm$ 0.58	1.95 $\pm$ 0.60	0.06	
1250.65 $\pm$ 0.81	1.41 $\pm$ 0.64	0.04	
1274.05 $\pm$ 0.18	7.42 $\pm$ 0.90	0.23	1367 --> 93
1299.89 $\pm$ 0.27	4.83 $\pm$ 0.71	0.15	3364 --> 2064
1367.76 $\pm$ 0.08	22.53 $\pm$ 1.54	0.71	1367 --> 0
1388.13 $\pm$ 0.24	6.45 $\pm$ 0.87	0.20	1482 --> 93
1482.17 $\pm$ 0.11	42.94 $\pm$ 2.82	1.35	1482 --> 0
1503.02 $\pm$ 0.67	2.71 $\pm$ 0.95	0.08	3446 --> 1942
1594.15 $\pm$ 0.17	12.16 $\pm$ 1.14	0.38	3831 --> 2236
1615.86 $\pm$ 0.09	72.89 $\pm$ 4.13	2.29	2657 --> 1042

¹Measured relative to the 93.6-keV transition ($I_{\gamma}=1000$).

²Calculated from relative intensities using the factor 0.0314 with 7% beta branching to the ground state of ^{91}Sr .

³Denotes transition identified only in coincidence.

Table 2. (Continued)

Energy (keV)	Relative Intensity ¹	Intensity per 100 Decays ²	Assignment (keV)
1624.77 ± 0.47	14.70 ± 1.01 ⁴	0.46	3364 --> 1740
1625.44 ± 0.32	21.17 ± 1.37 ⁴	0.66	2064 --> 439
1628.49 ± 0.14	26.80 ± 1.65	0.84	3693 --> 2064
1646.51 ± 0.23	7.68 ± 0.95	0.24	1740 --> 93
1711.98 ± 0.40	6.06 ± 1.19	0.19	3776 --> 2064
1719.91 ± 0.28	9.05 ± 1.35	0.28	2159 --> 439
1740.25 ± 0.10	41.80 ± 2.67	1.31	1740 --> 0
1766.17 ± 0.18	4.80 ± 1.23	0.15	3831 --> 2064
1794.51 ± 0.63	3.70 ± 1.14	0.12	4452 --> 2657
1823.30 ± 0.37	10.60 ± 1.80	0.33	1917 --> 93
1841.11 ± 0.28	3.76 ± 1.26	0.12	4078 --> 2236
1849.27 ± 0.09	97.91 ± 5.13	3.07	1942 --> 93
1859.56 ± 0.25	4.52 ± 0.92	0.14	3776 --> 1917
1874.41 ± 0.43	3.32 ± 1.59	0.10	3938 --> 2064
1917.11 ± 0.15	22.64 ± 1.72	0.71	1917 --> 0
1942.81 ± 0.17	11.82 ± 1.19	0.37	1942 --> 0
1952.96 ± 0.46	2.12 ± 0.92	0.07	3693 --> 1740
1970.99 ± 0.10	199.02 ± 10.37	6.24	2064 --> 93
2013.53 ± 0.33	7.87 ± 1.22	0.25	4078 --> 2064
2036.13 ± 0.28	10.92 ± 1.51	0.34	3776 --> 1740
2064.69 ± 0.14	23.25 ± 1.79	0.73	2064 --> 0
2143.22 ± 0.14	19.77 ± 1.47	0.62	2236 --> 93
2161.75 ± 0.55	3.47 ± 1.07	0.11	3643 --> 1482
2195.95 ± 0.43	5.52 ± 1.18	0.17	
2208.47 ± 0.71	3.12 ± 1.13	0.10	
2218.19 ± 0.30	8.29 ± 1.33	0.26	2657 --> 439
2236.86 ± 0.46	4.06 ± 1.03	0.13	2236 --> 0
2254.63 ± 0.35	3.69 ± 0.88	0.12	3736 --> 1482
2263.09 ± 0.33	4.54 ± 0.94	0.14	4327 --> 2064
2322.34 ± 0.21	13.30 ± 1.49	0.42	3364 --> 1042
2448.46 ± 0.73	4.35 ± 1.38	0.14	4390 --> 1942
2505.95 ± 0.14	42.23 ± 2.49	1.32	3736 --> 1230
2564.19 ± 0.14	372.34 ± 19.17	11.68	2657 --> 93
2606.71 ± 0.53	4.05 ± 1.05	0.13	
2724.20 ± 0.68	5.06 ± 1.52	0.16	
2783.34 ± 0.35	9.89 ± 1.45	0.31	4265 --> 1482
2789.64 ± 0.37	14.56 ± 1.51	0.46	4157 --> 1367

⁴Individual intensities split as determined from coincidence data.

Table 2. (Continued)

Energy (keV)	Relative Intensity ¹	Intensity per 100 Decays ²	Assignment (keV)
2847.39 ± 0.22	19.25 ± 1.97	0.60	4078 --> 1230
2872.54 ± 0.57	5.64 ± 1.65	0.18	4240 --> 1367
2897.62 ± 0.49	6.11 ± 1.18	0.19	4265 --> 1367
2911.95 ± 0.35	9.83 ± 0.66	0.31	
2925.72 ± 0.18	44.76 ± 2.82	1.40	3364 --> 439
2958.63 ± 0.55	3.81 ± 1.11	0.12	4189 --> 1230
2990.58 ± 0.51	5.98 ± 1.47	0.19	4358 --> 1367
3007.62 ± 0.49	8.13 ± 1.50	0.26	3446 --> 439
3107.90 ± 0.90	4.62 ± 1.60	0.14	
3147.30 ± 0.24	19.42 ± 1.86	0.61	4189 --> 1042
3224.35 ± 0.33	9.72 ± 1.06	0.30	5289 --> 2064
3270.90 ± 0.34	13.19 ± 1.81	0.41	3364 --> 93
3284.72 ± 0.81	4.82 ± 1.41	0.15	4327 --> 1042
3302.18 ± 0.96	4.05 ± 1.55	0.13	3395 --> 93
3337.82 ± 0.47	6.49 ± 1.74	0.20	3776 --> 439
3346.23 ± 0.58	5.31 ± 2.40	0.17	5289 --> 1942
3353.08 ± 0.59	6.00 ± 2.11	0.19	3446 --> 93
3376.49 ± 0.33	8.16 ± 3.59	0.26	
3395.36 ± 0.38	9.63 ± 1.71	0.30	3395 --> 0
3410.71 ± 0.77	2.40 ± 1.63	0.08	4452 --> 1042
3446.50 ± 0.20	43.94 ± 2.90	1.38	3446 --> 0
3599.67 ± 0.19	309.21 ± 16.14	9.70	3693 --> 93
3604.25 ± 0.62	10.65 ± 4.89	0.33	4043 --> 439
3639.14 ± 0.22	36.34 ± 2.79	1.14	4078 --> 439
3643.75 ± 0.23	23.25 ± 2.32	0.73	3643 --> 0
3682.90 ± 0.69	2.42 ± 1.32	0.08	3776 --> 93
3736.47 ± 0.37	17.07 ± 4.02	0.54	3736 --> 0
3745.93 ± 0.49	5.96 ± 1.35	0.19	3839 --> 93
3800.71 ± 0.49	4.50 ± 0.99	0.14	4240 --> 439
3839.25 ± 0.27	18.18 ± 1.91	0.57	3839 --> 0
3844.33 ± 0.25	30.20 ± 2.47	0.95	3938 --> 93
3888.43 ± 0.38	8.39 ± 1.08	0.26	4327 --> 439
3906.24 ± 0.92	2.81 ± 0.92	0.09	
3938.73 ± 0.53	5.38 ± 1.06	0.17	3938 --> 0
3949.56 ± 0.23	19.09 ± 1.62	0.60	4043 --> 93
3984.70 ± 0.26	12.29 ± 1.30	0.39	4078 --> 93
4043.26 ± 0.22	21.99 ± 1.56	0.69	4043 --> 0
4061.32 ± 0.51	3.44 ± 1.19	0.11	
4063.86 ± 0.66	1.33 ± 0.93	0.04	4157 --> 93
4078.25 ± 0.19	120.82 ± 6.38	3.79	4078 --> 0
4095.71 ± 0.33	7.10 ± 0.90	0.22	4189 --> 93

Table 2. (Continued)

Energy (keV)	Relative Intensity ¹	Intensity per 100 Decays ²	Assignment (keV)
4157.48 ± 0.22	20.81 ± 1.45	0.65	4157 --> 0
4171.66 ± 0.27	8.34 ± 0.86	0.26	4265 --> 93
4189.21 ± 0.30	6.86 ± 0.81	0.22	4189 --> 0
4224.77 ± 0.64	2.98 ± 0.61	0.09	
4234.06 ± 0.29	6.53 ± 0.68	0.20	4327 --> 93
4249.02 ± 0.28	10.08 ± 0.95	0.32	4249 --> 0
4253.71 ± 0.27	11.16 ± 1.05	0.35	4253 --> 0
4265.45 ± 0.21	42.54 ± 2.51	1.33	4265 --> 0
4297.09 ± 0.36	3.44 ± 0.50	0.11	4390 --> 93
4357.89 ± 0.73	1.55 ± 0.45	0.05	4358 --> 0
4391.25 ± 0.94	1.57 ± 0.45	0.05	4390 --> 0
4453.09 ± 0.38	4.27 ± 0.50	0.13	4452 --> 0
4544.07 ± 0.50	1.63 ± 0.39	0.05	
4699.30 ± 0.69	0.52 ± 0.32	0.02	4793 --> 93

A comparison of the most intense transitions is presented in Table 3 to show that the intensities from this work (relative to the 93.6-keV gamma ray which has been assigned an intensity of 1000) are about 30% less than those of Refs. (13) and (14). The most intense gamma ray is in an energy region where detector efficiency undergoes a rapid change. This causes difficulty in determining the correct intensities of other gamma rays relative to the normalization gamma ray. To resolve this discrepancy, independent measurements of the most intense peaks by both Weinbeck (28) and Hanson, et al. (29) with a large Ge(Li) and an additional measurement in the course of this study with a LEPS for which the efficiency was defined to within 5% over the region from 0 - 550 keV, were found to reproduce the intensities in Table 2.

The results from analyzing the Ge(Li)-Ge(Li) coincidence spectra for a total of 42 coincidence gates and their associated backgrounds are presented in Table 4. Previous coincidence studies are very limited by comparison, but there is a general consistency for the gates in common.

Several low-intensity transitions coincident with the 93.6-keV gamma ray were not seen in the coincidence spectrum due to the large ICC and the fact that the level at 93.6 keV is an isomeric state.

Table 3. Comparison of intensities with other ^{91}Rb studies¹

Energy (keV)	This work	Achterberg, <u>et al.</u> (14)	Mason and Johns (13)
93.63	1000 $\pm$ 51	1000 $\pm$ 100	1000
345.43	246 $\pm$ 12	340 $\pm$ 4	316
602.85	84 $\pm$ 4	102 $\pm$ 15	105
1137.24	115 $\pm$ 6	148 $\pm$ 15	124
1849.27	98 $\pm$ 5	147 $\pm$ 15	100
1970.99	199 $\pm$ 10	310 $\pm$ 30	258
2564.19	372 $\pm$ 19	576 $\pm$ 60	526
3599.67	309 $\pm$ 16	360 $\pm$ 40	368
4078.24	121 $\pm$ 6	160 $\pm$ 2	150

¹Relative intensity differences are largely due to different relative efficiency calibrations for the energy region near 100 keV. In this study several detectors with relative efficiencies known to within 5% consistently reproduced the intensities quoted in column 2.

Table 4. Coincidences in the decay of ^{91}Rb

Gate (keV)	Definite coincidences (keV)	Possible coincidences (keV)
94	345, 593, 603, 948, 1137, 1616, 1625, 1849, 1971, 2322, 2506, 2564, 3147	2014, 2218, 3354, 3600
345	94, 593, 603, 1023, 1616, 1625, 2322, 2926, 3147, 3639, 3888	3604
439	593, 603, 1023, 1616, 1625, 2926	3639
593	94, 345, 439, 603, 1023, 1042, 1625, 1971, 2065	1034
603	94, 345, 439, 593, 875, 1616, 3147	1023, 1300
875	94, 345, 439, 603, 948, 1042	
918	94, 1740	
948	94, 593, 1616	1023
1006	94, 1137	
1023	593, 603, 1042	
1042	593, 1023, 1616	875
1137	94, 2506, 2847	509, 1006, 1625
1206	1720	
1231	2506	1625
1300	94, 345, 1042, 1971	
1368	2790	
1388	94, 2783	

Table 4. (Continued)

Gate (keV)	Definite coincidences (keV)	Possible coincidences (keV)
1482	2783	
1616	94, 345, 439, 603, 948, 1042	
1625-8	94, 345, 439, 593, 948, 1042, 1740, 1971	
1646	94	
1712	439, 603, 948, 1971	
1720	94, 345, 439	
1740	918, 1625, 2036	
1849	94	
1971	94, 593, 1300, 1628, 2014	
2014	1971	
2036	1740	
2065	593	
2143	1594	
2218	94, 345, 439	
2322	603, 948, 1042	
2506	94, 1137	1231
2564	94	
2790	1368	
2847	94, 1137	1231
2926	94, 345, 439	
3008	345	

Table 4. (Continued)

Gate (keV)	Definite coincidences (keV)	Possible coincidences (keV)
3147	94, 345, 603, 948, 1042	439
3600-4	94, 345, 439	
3639	345, 439	94
3888	345	

A member of the 3600-3604-keV multiplet was observed to be coincident with the 345-keV gamma ray. The 3604-keV transition was the logical choice since the gamma ray at 3600 keV would cause an intensity imbalance for the 439.1-keV level.

Evidence for a gamma ray at 509.6 keV was observed in the 1137.2-keV gate. This transition was placed between two very definite levels and explains the presence of the 1624.8-keV transition in the 1137.2-keV gate.

The 1624-1625-1628-keV multiplet gate was observed to involve three distinct placements to further verify this as a triplet peak.

The transitions at 3395, 3446, 3736, 4043, 4078, 4157, 4249, 4254, and 4265 keV were not observed in the coincidence profile, indicating that they are transitions to the ground state.

Figure 10 displays the resulting level scheme for ^{91}Sr with 37 excited states assigning 109 of the gamma rays from the decay of ^{91}Rb . The proposed decay scheme is more extensive than those of Mason and Johns (13) or Achterberg, et al. (14). All levels were established by both energy sums and coincidences except for those at 3395, 3644, 3831, 3839, 3938, 4240, 4350, 4391, 4453, 4793, and 5289 keV which were established by energy sums only. Single transitions to the ground state establish the 4249- and 4254-keV levels.

Figure 10. The ^{91}Sr level scheme

Figure 10. The ^{91}Sr level scheme (continued)

B. The Decay of ^{91}Kr to Levels in ^{91}Rb

Figure 11 displays the gamma-ray singles spectrum for the decay of ^{91}Kr . Table 5 lists the energies of the 220 gamma rays assigned to this decay with their associated relative intensities. Most of the resulting energies agree with the other studies (13, 14) to within the quoted errors. Gamma rays at 556, 749, 1311, 1506, 1779, 1965, 2140, and 2620 keV with $I_\gamma > 10$ were not reported prior to this study. Multiplets which were previously identified as single peaks have been resolved at 822-825, 953-955, 992-995, 1025-1028, 1354-1356, 1456-1459, 1555-1557, 1725-1728, and 2555-2558-2559 keV.

A comparison of the relative intensities in Table 6 shows that although they are within the quoted errors a systematic deviation is likely. Additional measurements by Weinbeck (28) and Hanson, *et al.* (29) were in good agreement with the intensities reported in this work.

The results of the Ge(Li)-Ge(Li) coincidence measurements for a total of 84 coincidence spectra and their associated backgrounds are presented in Table 7. The number of gates investigated far exceeds any previous studies, but those few spectra in common are in agreement.

Coincidence intensities of the 894-895-keV peak in the 507- and 613-keV gates were used to apportion the intensity for each placement.

Figure 11. Gamma-ray spectrum from the decay of ^{91}Kr

Table 5. Gamma rays observed in the decay of ^{91}Kr

Energy (keV)	Relative Intensity ¹	Intensity per 100 Decays ²	Assignment (keV)
108.78 $\pm$ 0.04	1000.00 $\pm$ 57.56	43.17	108 --> 0
215.46 $\pm$ 0.22	4.07 $\pm$ 0.76	0.18	721 --> 506
384.29 $\pm$ 0.44	1.51 $\pm$ 0.55	0.07	3113 --> 2729
397.83 $\pm$ 0.13	36.02 $\pm$ 2.51	1.55	506 --> 108
400.67 $\pm$ 0.33	4.94 $\pm$ 1.17	0.21	2490 --> 2089
412.04 $\pm$ 0.08	54.07 $\pm$ 3.46	2.33	1133 --> 721
446.78 $\pm$ 0.06	37.96 $\pm$ 1.97	1.64	555 --> 108
450.78 $\pm$ 0.44	1.18 $\pm$ 0.37	0.05	1775 --> 1324
469.98 $\pm$ 0.50	1.48 $\pm$ 0.50	0.06	2559 --> 2089
474.63 $\pm$ 0.10	20.95 $\pm$ 1.44	0.90	2089 --> 1615
481.39 $\pm$ 0.09	28.48 $\pm$ 1.94	1.23	1615 --> 1133
489.49 $\pm$ 0.15	9.89 $\pm$ 1.28	0.43	1211 --> 721
501.97 $\pm$ 0.12	37.44 $\pm$ 6.28	1.62	502 --> 0
506.58 $\pm$ 0.07	441.18 $\pm$ 27.03	19.05	506 --> 0
541.88 $\pm$ 0.89	1.30 $\pm$ 0.74	0.06	2089 --> 1547
545.96 $\pm$ 0.11	9.40 $\pm$ 0.76	0.41	1267 --> 721
555.57 $\pm$ 0.07	44.73 $\pm$ 2.39	1.93	555 --> 0
569.00 $\pm$ 0.19	4.65 $\pm$ 0.62	0.20	4543 --> 3974
588.22 $\pm$ 0.07	20.73 $\pm$ 1.19	0.89	2089 --> 1501
612.87 $\pm$ 0.06	176.62 $\pm$ 9.38	7.63	721 --> 108
630.14 $\pm$ 0.07	50.66 $\pm$ 2.96	2.19	1136 --> 506
662.42 $\pm$ 0.07	29.40 $\pm$ 1.77	1.27	662 --> 0
671.46 $\pm$ 0.08	16.24 $\pm$ 1.18	0.70	1178 --> 506
679.97 $\pm$ 0.33	2.72 $\pm$ 0.72	0.12	1401 --> 721
712.39 $\pm$ 0.15	5.14 $\pm$ 0.58	0.22	1267 --> 555
721.55 $\pm$ 0.08	15.19 $\pm$ 1.02	0.66	721 --> 0
748.64 $\pm$ 0.08	13.08 $\pm$ 0.87	0.56	1304 --> 555
761.01 $\pm$ 0.08	23.92 $\pm$ 1.46	1.03	1267 --> 506
765.99 $\pm$ 0.87	1.19 $\pm$ 0.67	0.05	1267 --> 502
771.86 $\pm$ 0.16	8.00 $\pm$ 0.94	0.35	2861 --> 2089
780.18 $\pm$ 0.60	2.43 $\pm$ 0.94	0.10	1501 --> 721
785.25 $\pm$ 0.16	10.72 $\pm$ 1.17	0.46	2089 --> 1304
797.68 $\pm$ 0.15	5.56 $\pm$ 0.56	0.24	1304 --> 506
802.17 $\pm$ 0.15	2.84 $\pm$ 0.49	0.12	1304 --> 502
807.14 $\pm$ 0.09	13.17 $\pm$ 0.85	0.57	2844 --> 2037
814.04 $\pm$ 0.37	2.95 $\pm$ 0.72	0.13	2593 --> 1778

¹Measured relative to the 108.8-keV intensity ($I_{\gamma}=1000$).

²Calculated from relative intensities using the factor 0.0432 with 10% beta branching to the ground state of ^{91}Rb .

Table 5. (Continued)

Energy (keV)	Relative Intensity ¹	Intensity per 100 Decays ²	Assignment (keV)
817.64 ± 0.18	10.58 ± 0.98	0.46	1324 --> 506
822.14 ± 0.18	9.13 ± 0.92	0.39	2089 --> 1267
825.82 ± 0.16	9.43 ± 0.90	0.41	1547 --> 721
846.66 ± 0.43	2.47 ± 0.79	0.11	1401 --> 555
858.68 ± 0.22	5.87 ± 0.96	0.25	2861 --> 2002
874.92 ± 0.08	29.32 ± 1.58	1.27	2490 --> 1615
879.50 ± 0.28	2.87 ± 0.49	0.12	2381 --> 1501
893.60 ± 0.40	4.00 ± 1.00 ³	0.17	1615 --> 721
895.00 ± 0.50	6.60 ± 1.50 ³	0.28	1401 --> 506
900.47 ± 0.41	3.60 ± 0.90	0.16	2037 --> 1136
953.24 ± 0.16	7.56 ± 0.84	0.33	2089 --> 1136
955.74 ± 0.16	7.26 ± 0.83	0.31	2089 --> 1133
992.06 ± 0.57	2.85 ± 1.05	0.12	1547 --> 555
995.08 ± 0.12	18.43 ± 1.32	0.80	1501 --> 506
1008.98 ± 0.23	4.32 ± 0.66	0.19	3046 --> 2037
1024.91 ± 0.15	66.43 ± 4.97	2.87	1133 --> 108
1028.25 ± 0.28	15.45 ± 3.09	0.67	1136 --> 108
1041.80 ± 0.15	5.00 ± 0.60	0.22	3044 --> 2002
1058.90 ± 0.15	6.15 ± 0.60	0.27	2195 --> 1136
1069.00 ± 0.30	2.00 ± 0.50	0.09	1178 --> 108*
1085.89 ± 0.33	2.72 ± 0.52	0.12	4199 --> 3113
1091.61 ± 0.14	7.94 ± 0.67	0.34	2593 --> 1501
1102.18 ± 0.15	17.44 ± 1.75	0.75	1211 --> 108
1108.68 ± 0.10	164.75 ± 8.61	7.11	1615 --> 506
1129.81 ± 0.62	2.50 ± 0.92	0.11	3974 --> 2844
1136.81 ± 0.14	23.83 ± 1.92	1.03	1136 --> 0
1158.77 ± 0.67	2.38 ± 1.08	0.10	1267 --> 108
1178.03 ± 0.11	29.55 ± 1.60	1.28	1178 --> 0
1195.42 ± 0.20	5.98 ± 0.61	0.26	1304 --> 108
1198.90 ± 0.52	2.20 ± 0.60	0.09	2377 --> 1178
1202.23 ± 0.38	2.73 ± 0.55	0.12	4129 --> 2926
1215.57 ± 0.14	15.17 ± 1.24	0.66	1324 --> 108
1227.49 ± 0.22	2.81 ± 0.54	0.12	4072 --> 2844
1231.14 ± 0.28	1.20 ± 0.50	0.05	3206 --> 1975
1247.35 ± 0.36	4.01 ± 0.95	0.17	4211 --> 2964
1267.83 ± 0.13	15.34 ± 1.13	0.66	1267 --> 0

³Individual intensities split as determined from coincidence data.

*Denotes transition identified only in coincidence.

Table 5. (Continued)

Energy (keV)	Relative Intensity ¹	Intensity per 100 Decays ²	Assignment (keV)
1277.00 ± 0.40	4.80 ± 0.80	0.21	1778 --> 502
1281.11 ± 0.15	14.17 ± 1.09	0.61	2002 --> 721
1292.95 ± 0.17	11.20 ± 1.20	0.48	1401 --> 108
1304.28 ± 0.13	28.77 ± 1.88	1.24	1304 --> 0
1311.34 ± 0.21	10.22 ± 1.17	0.44	3090 --> 1778
1315.54 ± 0.17	13.54 ± 1.27	0.58	2037 --> 721
1324.22 ± 0.18	12.62 ± 1.18	0.54	1324 --> 0
1327.25 ± 0.61	2.98 ± 0.94	0.13	2964 --> 1637
1337.99 ± 0.36	4.00 ± 0.78	0.17	3113 --> 1775
1353.54 ± 0.21	13.75 ± 1.96	0.59	2490 --> 1136
1356.17 ± 0.18	17.17 ± 2.01	0.74	2490 --> 1133
1359.63 ± 0.22	5.04 ± 1.10	0.22	2861 --> 1501
1365.29 ± 0.48	5.27 ± 1.28	0.23	3002 --> 1637
1368.46 ± 0.33	7.73 ± 1.33	0.33	2089 --> 721
1386.99 ± 0.17	12.59 ± 1.25	0.54	3002 --> 1615
1392.74 ± 0.17	12.57 ± 1.22	0.54	1501 --> 108
1401.99 ± 0.32	5.18 ± 1.07	0.22	1401 --> 0
1419.72 ± 0.13	19.36 ± 1.33	0.84	1975 --> 555
1426.12 ± 0.58	2.40 ± 0.80	0.10	2559 --> 1133
1439.11 ± 0.21	8.27 ± 0.93	0.36	1547 --> 108
1456.50 ± 0.50	8.10 ± 2.30	0.35	2593 --> 1136
1458.98 ± 0.68	6.50 ± 1.80	0.28	2593 --> 1133
1468.17 ± 0.55	3.66 ± 0.89	0.16	1975 --> 506
1474.59 ± 0.45	2.00 ± 0.60	0.09	2195 --> 721
1479.90 ± 0.21	12.39 ± 1.36	0.54	4698 --> 3218
1500.60 ± 0.50	16.00 ± 2.00 ³	0.69	3002 --> 1501
1501.60 ± 0.11	111.10 ± 6.50 ³	4.80	1501 --> 0
1506.40 ± 0.40	18.60 ± 4.20	0.80	1615 --> 108
1517.83 ± 0.52	2.00 ± 0.60	0.09	2729 --> 1211
1524.95 ± 0.48	3.68 ± 0.87	0.16	2926 --> 1401
1528.29 ± 0.14	20.89 ± 1.42	0.90	1637 --> 108
1537.34 ± 0.24	7.60 ± 1.00	0.33	2861 --> 1324
1547.65 ± 0.25	8.41 ± 1.14	0.36	1547 --> 0
1555.26 ± 0.39	14.26 ± 4.43	0.62	3056 --> 1501
1557.21 ± 0.51	10.94 ± 4.40	0.47	2861 --> 1304
1563.60 ± 0.40	4.00 ± 0.80	0.17	4543 --> 2979
1577.55 ± 0.58	2.15 ± 0.66	0.09	2979 --> 1401
1583.51 ± 0.19	8.81 ± 0.83	0.38	2089 --> 506
1589.18 ± 0.51	2.53 ± 0.67	0.11	3090 --> 1501
1614.07 ± 0.14	23.80 ± 1.72	1.03	1722 --> 108
1626.73 ± 0.35	7.47 ± 2.16	0.32	4683 --> 3056

Table 5. (Continued)

Energy (keV)	Relative Intensity ¹		Intensity per 100 Decays ²	Assignment (keV)
1633.51 ± 0.74	3.28 ±	2.48	0.14	2844 --> 1211
1650.22 ± 0.24	3.87 ±	0.75	0.17	2861 --> 1211
1659.40 ± 0.52	2.36 ±	0.64	0.10	2964 --> 1304
1666.73 ± 0.13	6.20 ±	1.45 ³	0.27	2844 --> 1178
1666.73 ± 0.13	18.10 ±	1.45 ³	0.78	1775 --> 108
1675.83 ± 0.19	8.82 ±	0.82	0.38	2979 --> 1304
1681.24 ± 0.33	3.97 ±	0.67	0.17	4683 --> 3002
1697.56 ± 0.52	3.35 ±	1.06	0.14	3002 --> 1304
1710.02 ± 0.35	5.60 ±	1.80	0.24	3325 --> 1615
1725.23 ± 0.29	4.43 ±	0.97	0.19	2861 --> 1136
1727.85 ± 0.16	11.53 ±	0.88	0.50	2861 --> 1133
1741.78 ± 0.13	18.50 ±	1.40	0.80	2919 --> 1178
1752.87 ± 0.29	4.27 ±	0.73	0.18	2964 --> 1211
1778.85 ± 0.16	18.89 ±	1.48	0.82	1778 --> 0
1783.35 ± 0.26	8.66 ±	1.13	0.37	2919 --> 1136
1789.43 ± 0.21	9.40 ±	1.00	0.41	3113 --> 1324
1823.05 ± 0.24	6.80 ±	0.80	0.29	3090 --> 1267
1827.08 ± 0.39	4.73 ±	0.87	0.20	2964 --> 1136
1834.56 ± 0.39	3.00 ±	0.60	0.13	4211 --> 2377
1843.09 ± 0.56	2.90 ±	0.80	0.13	2979 --> 1136
1856.59 ± 0.80	1.89 ±	0.76	0.08	4543 --> 2686
1866.21 ± 0.33	3.80 ±	0.80	0.16	1975 --> 108
1871.75 ± 0.33	4.40 ±	1.30	0.19	2593 --> 721
1874.99 ± 0.24	10.90 ±	1.37	0.47	2381 --> 506
1880.10 ± 0.38	5.55 ±	0.96	0.24	3090 --> 1211
1884.25 ± 0.79	2.42 ±	0.89	0.10	3974 --> 2089
1913.94 ± 0.83	1.50 ±	0.70	0.06	3218 --> 1304
1965.11 ± 0.19	15.30 ±	1.40	0.66	2686 --> 721
1982.74 ± 0.49	3.76 ±	0.92	0.16	2490 --> 506
1995.00 ± 0.80	1.00 ±	0.50	0.04	3206 --> 1211 ⁴
2004.05 ± 0.90	0.85 ±	0.90	0.04	2559 --> 555
2039.36 ± 0.24	8.86 ±	0.99	0.38	4129 --> 2089
2057.27 ± 0.18	9.55 ±	0.76	0.41	2559 --> 502
2072.25 ± 0.25	7.08 ±	0.98	0.31	3206 --> 1133
2086.99 ± 0.41	4.00 ±	1.00	0.17	2195 --> 108
2139.98 ± 0.21	16.36 ±	1.75	0.71	2861 --> 721
2195.99 ± 0.23	8.06 ±	0.98	0.35	2195 --> 0
2242.50 ± 0.25	3.90 ±	0.60	0.17	2964 --> 721
2251.41 ± 0.49	3.28 ±	0.85	0.14	3974 --> 1722
2268.60 ± 0.39	5.22 ±	1.10	0.23	2377 --> 108
2281.05 ± 0.58	3.41 ±	1.09	0.15	3002 --> 721
2322.64 ± 0.79	2.47 ±	1.03	0.11	3044 --> 721

Table 5. (Continued)

Energy (keV)	Relative Intensity ¹	Intensity per 100 Decays ²	Assignment (keV)
2377.34 ± 0.23	8.20 ± 0.76	0.35	2377 --> 0
2381.87 ± 0.24	5.00 ± 0.70	0.22	2381 --> 0
2391.79 ± 0.86	2.55 ± 0.95	0.11	3113 --> 721
2395.08 ± 0.74	2.96 ± 0.96	0.13	3056 --> 662
2413.69 ± 0.31	7.80 ± 1.09	0.34	2919 --> 506
2425.00 ± 0.71	3.38 ± 1.01	0.15	2926 --> 502
2447.26 ± 0.65	5.65 ± 1.64	0.24	3002 --> 555
2450.69 ± 0.27	15.59 ± 1.85	0.67	2559 --> 108
2457.67 ± 0.32	8.09 ± 1.18	0.35	2964 --> 506
2473.06 ± 0.48	9.37 ± 2.01	0.40	2979 --> 506
2479.98 ± 0.69	4.90 ± 1.36	0.21	4569 --> 2089
2484.35 ± 0.13	64.15 ± 3.75	2.77	2593 --> 108
2495.82 ± 0.22	15.87 ± 1.51	0.69	3002 --> 506
2539.40 ± 0.32	3.91 ± 0.52	0.17	3046 --> 506
2550.64 ± 0.37	4.21 ± 0.53	0.18	3056 --> 506
2555.80 ± 0.60	2.20 ± 1.00 ³	0.09	3218 --> 662
2558.00 ± 0.40	4.00 ± 1.50 ³	0.17	3113 --> 555
2559.40 ± 0.40	8.10 ± 1.30 ³	0.35	2559 --> 0
2585.64 ± 0.48	2.30 ± 0.60	0.10	3910 --> 1324
2593.15 ± 0.20	12.45 ± 1.15	0.54	2593 --> 0
2606.93 ± 0.47	5.58 ± 1.05	0.24	3113 --> 506
2620.33 ± 0.23	15.54 ± 1.43	0.67	2729 --> 108
2627.72 ± 0.79	4.02 ± 0.52	0.17	4129 --> 1501
2642.53 ± 0.35	4.67 ± 0.79	0.20	3910 --> 1267
2663.03 ± 0.72	1.96 ± 0.60	0.08	3218 --> 555
2686.98 ± 0.94	2.08 ± 0.96	0.09	2686 --> 0
2732.10 ± 0.73	5.52 ± 1.69	0.24	3910 --> 1178
2735.83 ± 0.19	33.95 ± 2.59	1.47	2844 --> 108
2752.59 ± 0.19	17.04 ± 1.44	0.74	2861 --> 108
2769.38 ± 0.50	4.79 ± 1.18	0.21	3325 --> 555
2809.94 ± 1.15	2.79 ± 1.62	0.12	4211 --> 1401
2811.72 ± 0.59	6.15 ± 0.69	0.27	2919 --> 108
2844.98 ± 0.32	7.69 ± 1.15	0.33	2844 --> 0
2855.28 ± 0.29	9.32 ± 1.19	0.40	2964 --> 108
2870.54 ± 0.21	19.57 ± 1.72	0.85	2979 --> 108
2893.47 ± 0.27	9.18 ± 1.13	0.40	3002 --> 108
2904.37 ± 1.09	1.70 ± 0.92	0.07	4683 --> 1778
2919.91 ± 0.37	6.16 ± 1.01	0.27	2919 --> 0
2926.70 ± 0.52	2.00 ± 0.70	0.09	2926 --> 0
2930.78 ± 0.52	4.47 ± 1.00	0.19	4545 --> 1615
2966.61 ± 0.71	2.93 ± 0.84	0.13	3687 --> 721
2981.85 ± 0.19	29.99 ± 1.90	1.29	3090 --> 108

Table 5. (Continued)

Energy (keV)	Relative Intensity ¹	Intensity per 100 Decays ²	Assignment (keV)
3001.87 ± 0.80	5.91 ± 2.08	0.26	3002 --> 0
3005.09 ± 0.97	2.55 ± 3.49	0.11	3113 --> 108
3041.28 ± 1.03	2.93 ± 1.27	0.13	4543 --> 1501
3043.68 ± 0.93	1.20 ± 1.05	0.05	3044 --> 0
3052.63 ± 1.12	3.63 ± 1.89	0.16	
3056.80 ± 0.22	20.00 ± 2.00	0.86	3056 --> 0
3097.40 ± 0.28	8.38 ± 0.90	0.36	3206 --> 108
3109.56 ± 0.51	8.32 ± 1.83	0.36	3218 --> 108
3113.50 ± 0.20	49.38 ± 2.94	2.13	3113 --> 0
3180.90 ± 0.75	2.47 ± 0.85	0.11	3687 --> 506
3265.36 ± 1.03	1.35 ± 0.54	0.06	4569 --> 1304
3324.93 ± 0.37	4.98 ± 0.74	0.21	3325 --> 0
3393.60 ± 0.33	6.47 ± 0.79	0.28	4698 --> 1304
3403.39 ± 0.49	3.70 ± 0.75	0.16	3910 --> 506
3435.66 ± 0.96	2.22 ± 0.90	0.10	4569 --> 1133
3444.43 ± 0.49	4.89 ± 1.03	0.21	
3490.02 ± 1.07	1.65 ± 0.76	0.07	4211 --> 721
3578.35 ± 0.53	2.53 ± 0.58	0.11	3687 --> 108
3704.95 ± 1.06	1.48 ± 0.55	0.06	4211 --> 506
3910.00 ± 1.10	1.10 ± 0.40	0.05	3910 --> 0
3973.85 ± 0.95	1.14 ± 0.40	0.05	3974 --> 0
4129.32 ± 0.97	1.20 ± 0.44	0.05	4129 --> 0
4199.61 ± 0.80	1.69 ± 0.45	0.07	4199 --> 0
4436.77 ± 0.63	1.64 ± 0.33	0.07	4545 --> 108

Table 6. Comparison of intensities with other ^{91}Kr studies

Energy (keV)	This work	Achterberg, <u>et al.</u> (14)
108.78	1000 $\pm$ 58	1000 $\pm$ 100
506.58	441 $\pm$ 27	400 $\pm$ 60
612.87	177 $\pm$ 9	150 $\pm$ 16
1108.68	165 $\pm$ 9	164 $\pm$ 16
1501(doublet)	127 $\pm$ 8	151 $\pm$ 16
2484.35	64 $\pm$ 4	72 $\pm$ 8
3113.50	49 $\pm$ 3	57 $\pm$ 6

Table 7. Coincidences in the decay of ^{91}Kr

Gate (keV)	Definite coincidences (keV)	Possible coincidences (keV)
109	398, 412, 447, 481, 489, 588, 613, 749, 807, 818, 826, 875, 1025, 1028, 1102, 1109, 1195, 1216, 1281, 1293, 1316, 1368, 1393, 1420, 1439, 1506, 1528, 1614, 1667, 2140, 2269, 2451, 2484, 2620, 2736, 2753, 2871, 2893, 2982, 3097	215, 546, 630, 859, 894, 953, 1069, 1092, 1159, 1354, 1356, 1866, 1880, 2242, 2281, 2558, 2812, 2855
398	109, 475, 588, 630, 671, 761, 772, 807, 818, 822, 875, 995, 1109, 1354, 1387, 1710, 1783, 2140, 2496, 2607	215, 798, 1456, 1584, 1627
412	109, 481, 613, 722, 1356, 1728	956, 1995, 2072
447	109, 712, 749, 992, 1557	1420, 2004, 2447, 2558
475	398, 481, 507, 613, 772, 1025, 1109	412, 894
481	412, 475, 875, 1025, 1387	507
489	613, 1634, 1753	722, 1650, 1880, 1995
502	802, 1277, 2057	766
507	215, 475, 630, 671, 761, 798, 818, 875, 995, 1059, 1109, 1354, 1387, 1537, 1584, 1742, 1783, 1789, 1827, 1875, 2414, 2458, 2473, 2496, 2607	481, 489, 953, 1316, 1456, 1468, 1710, 2539, 2551
546	109, 613, 722, 822	1823
556	712, 749, 992, 1420	542, 847, 2004, 2447, 2558

Table 7. (Continued)

Gate (keV)	Definite coincidences (keV)	Possible coincidences (keV)
588	772, 995, 1502	1393
613	109, 412, 481, 489, 546, 780, 807, 826, 859, 894, 1281, 1316, 1368, 1426, 1872, 1880, 1965, 2140, 2967	2242, 2281, 2323
630	109, 398, 507, 953, 1354, 1456, 1783	900, 1059, 1827
662	2395	
671	109, 398, 507, 1742	1667
712	109, 447, 556	
722	412, 807, 1316	894, 1281, 2140
749	109, 447, 556, 785, 1557, 1676	
761	398, 507, 772, 822	1823
772	475, 588, 822	1109
785	447, 556, 749, 1304	
798	109, 398, 507, 1676	785, 1557
807	613, 722, 1130, 1316	
818	398, 507	1537, 1789
822	398, 447, 507, 546, 712	556, 613, 772
826	109, 613	
859	613, 722, 1281	
875	109, 398, 481, 507, 1109, 1506	894

Table 7. (Continued)

Gate (keV)	Definite coincidences (keV)	Possible coincidences (keV)
894-5	109, 475, 506, 613	875
995	109, 398, 507, 588, 1092, 1555	1501
1009	613, 900, 1316	
1025	109, 481, 875, 1356, 1426, 1728	956, 2072
1028	109, 1354, 1456, 1783	953
1042	109, 507	398
1102	109, 1634, 1650	1880
1109	109, 398, 475, 507, 875, 1387	
1178	1667, 1742	
1195	109, 1557	
1216	109, 1537, 1789	
1268	822	
1277		502
1281	109, 507, 613, 722, 859	
1293	109	
1304	785, 1557	1676, 1753
1316	109, 613, 807	
1324		1537
1354	109, 398, 507, 630, 1137	1028
1356	109, 398, 412, 507, 613	1025

Table 7. (Continued)

Gate (keV)	Definite coincidences (keV)	Possible coincidences (keV)
1368	109, 613, 722, 772	
1387	507, 1109	
1393	109, 588, 1092	
1420	109, 447, 556	
1426	613	
1439	109	
1456	507, 630	
1458	412, 613	
1502	588, 1092, 1360, 1501, 1555, 1589	
1506	109	
1528	109	
1537	507, 818, 1216, 1324	109, 398
1555	109, 398, 507, 1502	995
1557	556, 749, 1304	798, 802
1614	109	1281
1667	109	507, 671, 1178, 1227, 1338
1676	556, 749, 798, 1304	109, 447, 507
1742	109, 507, 671	1069, 1178
1779	814	
1783	507, 630, 1137	
1789	507, 1216, 1324	818

Table 7. (Continued)

Gate (keV)	Definite coincidences (keV)	Possible coincidences (keV)
1823	507, 1268	761
1827	507, 630	1028
1875	507	109, 398
1880	109, 489, 507, 613	1102
1965	109, 613	
2057	502	
2140	109, 613	
2451	109	
2484	109	
2496	109, 398, 507	
2736	109	
2753	109	
2871	109	
2982	109	

The 1502-keV gate was discovered to be in coincidence with a peak at approximately the same energy. Once the 3002-keV level was established, the appropriate intensity for the 1501-keV gamma ray was found by comparing the coincidence intensity with other gamma rays seen in the 1502-keV gate. The 1502-keV gamma-ray intensity was reduced by the total intensity for the 1501-keV gamma ray.

The 1667-keV gamma ray was observed to have two placements due to the very definite coincidence with the 109-keV gamma ray and lesser coincidences with the 671- and 1178-keV gamma rays. Apportionment of the intensity for this peak also eliminated an otherwise troublesome intensity imbalance for the 1178-keV level.

Gamma rays at 1069 and 1995 keV were not seen in singles but did appear in the 109- and 489-keV gates, respectively. The intensities were assigned from coincidence intensity comparisons. The transitions at 3057 and 3114 keV were not observed in the coincidence profiles indicating that they are transitions into the ground state.

Figure 12 displays the proposed level scheme for ^{91}Rb in which 218 gamma rays are assigned to a scheme consisting of 60 excited states. The scheme is remarkable in that it includes nearly every gamma ray observed from the decay of ^{91}Kr and more than half of the assignments were made on the basis of strong coincidence information.

Figure 12. The ^{91}Rb level scheme

Figure 12. The ^{91}Rb level scheme (continued)

Figure 12. The ^{91}Rb level scheme (continued)

Most of the levels are the result of several definite coincidences and energy sums. Exceptions to these are levels at 2003, 2687, 2729, and 4072 keV which were established by one definite coincidence and fewer than three energy sums. Levels at 4199, 4546, and 4698 keV were established by energy sums only.

C. Internal-Conversion Coefficient Results

Figure 13 shows a ^{91}Kr enhanced spectrum in part (a) and a ^{91}Rb enhanced spectrum in part (b) used for measuring the internal-conversion coefficients (ICC's) of the 108.8-keV and 93.6-keV transitions, respectively, by the XPG method. Compared to equilibrium mass 91 activity, the enhancements were a factor of 50 for the decay of ^{91}Kr and 100 for the decay of ^{91}Rb . The determination of K-shell ICC's required corrections in the observed X-ray intensity for contributions from the X rays due to ^{90}Kr hydride contaminant and the non-enhanced mass 91 activity. For ^{91}Kr and ^{91}Rb decays, less than 0.5% of the K-shell X rays were due to other gamma rays. For the ^{90}Kr decay, the K-shell ICC is 0.159 for the 121.7-keV doublet from ^{90}Kr which represents 92% of the X rays seen in ^{90}Kr decay. Correcting for the non-enhanced mass 91 activity required a few iterations using deduced ICC values for the 108.8-keV and 93.6-keV transitions.

Figure 13. X-ray and gamma-ray spectra for mass 91 with (a) ^{91}Kr activity enhanced and (b) ^{91}Rb activity enhanced

A normalized-electron-peak-to-gamma-peak (NPG) measurement by Weinbeck (28) determined the 93-keV K/L ratio and the equilibrium 93K/108K ratio of the K-shell ICC's. These ICC values are presented in Table 8 and are compared to the values reported by Achterberg, et al. (14) and the theoretical ICC values.

The resulting K-shell coefficients indicate the 93.6-keV transition in ^{91}Sr to be of essentially pure E2 multipolarity and the 108.8-keV transition in ^{91}Rb to be of essentially pure M1 multipolarity. Thus, no change in parity occurs for either transition which agrees with predictions of the spherical shell model for nuclei which have only a few nucleons outside of closed shells. This also agrees with the systematics of similar nuclei in this region. The hypothesis of Achterberg, et al. (14) that the 108.8-keV excited state was due to a stable deformation is shown by our results to have no basis in fact (30).

The sums of the K-, L-, and M-shell conversion coefficients for both the E2 transition in ^{91}Sr and the M1 transition in ^{91}Rb yield total ICC's of 1.298 ± 0.106 and 0.115 ± 0.007 , respectively. Both values are slightly larger than measurements by Achterberg, et al. (14) and Malmkog and McDonald (15).

Table 8. Internal-conversion coefficients

Transition ¹	Experimental values				Theoretical ²		
	Achterberg, <u>et al.</u> (14)	NPG	Present study		E1	M1	E2
			XPG	mean			
93K	1.05 ±0.10	1.19 ±0.06	1.01 ±0.07	1.10 ±0.09	0.109	0.172	1.09
93K/L	----	5.95	----	----	9.01	8.78	5.99
108K	0.067 ±0.012	----	0.108 ±0.011	0.109 ³ ±0.007	0.066	0.101	0.61
93K/108K	15.7 ±3.2	10.1 ±0.5	9.4 ±1.2	10.0 ⁴ ±0.3	-----	-----	-----

¹Transitions labelled by energy in keV and atomic shell.

²R. S. Hager and E. C. Seltzer (25).

³Mean value obtained from XPG result and the result found by dividing the 93K mean value by the 93K/108K mean value.

⁴Mean value obtained by averaging the NPG and XPG values together with the value of 10.1 ± 0.5 found by Halbig (31).

D. Ground-state Beta Branchings

In order to calculate the ground-state beta branchings, the areas of several peaks from each of the decaying nuclides in the equilibrium spectra were found. The peak fitting was limited to the most intense peaks from each decay with least interference from other peaks. The 398-, 412-, 447-, 507-, 613-, 662-, and 875-keV peaks from the decay of ^{91}Kr , the 345-, 439-, 593-, and 603-keV peaks from the decay of ^{91}Rb , and the 653-, 750-, 926-, and 1024-keV peaks from the decay of ^{91}Sr were analyzed from each of the 30-minute collection intervals.

The relative gamma-ray intensity of a particular gamma ray during a time interval was calculated by correcting for system dead time during each time interval and the detector efficiency for that gamma ray. Ratios of excited-state-to-ground-state transitions per transition for a particular gamma ray were multiplied by the calculated relative intensity to determine the number of observed gamma-ray transitions into the ground state. The weighted averages of the relative numbers of excited-to-ground-state transitions per minute are given in Table 9 for each decaying nuclide. Figure 14 shows a spectrum from the equilibrium activities of ^{91}Kr and ^{91}Rb .

Since the decay behavior of ^{91}Sr is known (22, 26), the numbers in Table 9 for the decays of ^{91}Kr and ^{91}Rb during

Table 9. Gamma-ray transitions into the ground states of mass 91 nuclides vs. time

Time (min)	Decaying nuclide					
	⁹¹ Kr ¹		⁹¹ Rb ²		⁹¹ Sr ³	
	cts/min	% unc	cts/min	% unc	cts/min	% unc
7-37	2658	4.2	2741	3.4	---	---
38-68	2336	4.3	2440	3.5	118	8.5
69-99	2175	4.8	2309	4.3	192	5.4
100-130	2809	6.8	2954	4.5	254	6.4
132-162	----	---	----	---	265	4.4
163-193	----	---	----	---	254	4.2
194-224	----	---	----	---	242	4.0
225-255	----	---	----	---	230	4.4
256-286	----	---	----	---	224	4.2
287-317	----	---	----	---	214	4.3
318-348	----	---	----	---	206	4.1

¹The level scheme for ⁹¹Kr decay indicates 2084 transitions (excluding beta rays) into the ground state per 1000 gamma rays at 108.8 keV.

²The level scheme for ⁹¹Rb decay indicates 2965 transitions (excluding beta rays) into the ground state per 1000 gamma rays at 93.6 keV.

³The level scheme for ⁹¹Sr decay has a ground-state beta branching of 30.8% according to Ref. (22).

Figure 14. Low energy gamma-ray spectrum for the equilibrium decays of ^{91}Kr and ^{91}Rb .

the four initial 30-minute intervals and for the decay of ^{91}Sr during the remaining 30-minute intervals were used to calculate the total number of decays into and out of each ground state at equilibrium. The calculation involved integrating the activity equations for the three decaying nuclides using the numbers of excited-state-to-ground-state transitions to determine the relative numbers of such transitions at equilibrium.

The values for beta branchings into the ground states of ^{91}Rb and ^{91}Sr from the equilibrium data were $(8 \pm 5) \%$ and $(5 \pm 5) \%$, respectively. Averaging these values with the results from 4π -scintillation detector studies by Hanson, et al. (29) of $(12 \pm 6) \%$ for ^{91}Kr decay and less than 28% for ^{91}Rb decay gives an average value for these beta branchings of $(10 \pm 5) \%$ to ^{91}Rb and $(7 \pm 5) \%$ to ^{91}Sr . Not surprisingly, both values are in disagreement with those of Achterberg, et al. (14). This disagreement is a reflection of several unreported transitions, different relative intensities, and using incomplete level schemes in Ref. (14).

E. Beta Branchings and $\log f_t$ Values for
Levels in ^{91}Sr and ^{91}Rb

The level energies for the 38 levels in ^{91}Sr , which are presented in Table 10, were determined from weighted averages of all gamma-ray transitions into and out of each level. In addition, statistical uncertainties of energies, percentages of absolute beta branchings, and values of $\log f_t$ and $\log f_{1t}$ are presented.

The absolute beta branchings were determined from level scheme intensity imbalances with the gamma-ray intensities from Section A, the total ICC for the 93.6-keV transition from Section C, and the ground-state beta branching from Section D. Values of $\log f_t$ and $\log f_{1t}$ were calculated from the absolute beta branchings to each level and the reported Q-value from Clifford, *et al.* (9).

Table 11 presents the energies, statistical uncertainties, absolute beta branchings, and the values of $\log f_t$ and $\log f_{1t}$ for the 61 levels in the ^{91}Rb level scheme. Intensity imbalances from Section B, total ICC for the 108.8-keV transition from Section C, ground-state beta branching from Section D, and the Q-value from Clifford, *et al.* were used.

Table 10. Beta branchings and $\log ft$ values for ^{91}Rb decay

^{91}Sr Levels (keV)	Percent Beta Branching	$\log ft$	$\log f_{1t}$
0.00 $\pm$ 0.00	7.00 $\pm$ 5.00	7.30 $\pm$ 0.31	9.21
93.64 $\pm$ 0.04	23.49 $\pm$ 4.13	6.74 $\pm$ 0.08	8.64
439.13 $\pm$ 0.06	2.14 $\pm$ 0.50	7.66 $\pm$ 0.10	9.50
1042.02 $\pm$ 0.10	1.72 $\pm$ 0.27	7.51 $\pm$ 0.07	9.26
1230.83 $\pm$ 0.09	1.60 $\pm$ 0.25	7.46 $\pm$ 0.07	9.18
1367.75 $\pm$ 0.07	< 0.03	> 9.08	10.76
1482.10 $\pm$ 0.14	1.01 $\pm$ 0.13	7.55 $\pm$ 0.06	9.22
1740.25 $\pm$ 0.09	0.67 $\pm$ 0.12	7.61 $\pm$ 0.08	9.22
1917.07 $\pm$ 0.12	1.00 $\pm$ 0.11	7.35 $\pm$ 0.05	8.93
1942.88 $\pm$ 0.10	3.05 $\pm$ 0.28	6.85 $\pm$ 0.04	8.42
2064.74 $\pm$ 0.22	4.71 $\pm$ 0.48	6.60 $\pm$ 0.05	8.15
2159.06 $\pm$ 0.23	0.18 $\pm$ 0.05	7.98 $\pm$ 0.12	9.50
2236.92 $\pm$ 0.11	0.33 $\pm$ 0.08	7.66 $\pm$ 0.11	9.16
2657.83 $\pm$ 0.20	15.27 $\pm$ 1.20	5.75 $\pm$ 0.04	7.16
3364.65 $\pm$ 0.20	2.68 $\pm$ 0.22	6.02 $\pm$ 0.04	7.22
3395.42 $\pm$ 0.36	0.43 $\pm$ 0.08	6.79 $\pm$ 0.08	7.98
3446.51 $\pm$ 0.18	1.91 $\pm$ 0.18	6.10 $\pm$ 0.04	7.27
3643.72 $\pm$ 0.20	0.78 $\pm$ 0.10	6.33 $\pm$ 0.06	7.42
3693.19 $\pm$ 0.14	10.73 $\pm$ 0.88	5.14 $\pm$ 0.04	6.22
3736.73 $\pm$ 0.14	1.98 $\pm$ 0.20	5.84 $\pm$ 0.05	6.90
3776.60 $\pm$ 0.19	0.95 $\pm$ 0.12	6.12 $\pm$ 0.06	7.16
3831.09 $\pm$ 0.25	0.63 $\pm$ 0.07	6.25 $\pm$ 0.05	7.27
3839.33 $\pm$ 0.24	0.76 $\pm$ 0.09	6.16 $\pm$ 0.06	7.18
3938.30 $\pm$ 0.49	1.22 $\pm$ 0.13	5.86 $\pm$ 0.05	6.83
4043.25 $\pm$ 0.14	1.52 $\pm$ 0.20	5.65 $\pm$ 0.06	6.58
4078.24 $\pm$ 0.10	6.28 $\pm$ 0.48	5.00 $\pm$ 0.04	5.91
4157.46 $\pm$ 0.18	1.15 $\pm$ 0.11	5.65 $\pm$ 0.05	6.52
4189.30 $\pm$ 0.16	1.17 $\pm$ 0.11	5.61 $\pm$ 0.05	6.46
4240.03 $\pm$ 0.37	0.32 $\pm$ 0.06	6.11 $\pm$ 0.09	6.94
4249.02 $\pm$ 0.28	0.32 $\pm$ 0.04	6.10 $\pm$ 0.06	6.93
4253.71 $\pm$ 0.27	0.35 $\pm$ 0.04	6.05 $\pm$ 0.06	6.88
4265.39 $\pm$ 0.15	2.10 $\pm$ 0.17	5.26 $\pm$ 0.04	6.08
4327.64 $\pm$ 0.24	0.76 $\pm$ 0.08	5.63 $\pm$ 0.05	6.41
4358.30 $\pm$ 0.21	0.52 $\pm$ 0.06	5.76 $\pm$ 0.06	6.52
4390.89 $\pm$ 0.30	0.29 $\pm$ 0.05	5.96 $\pm$ 0.08	6.71
4452.88 $\pm$ 0.31	0.33 $\pm$ 0.07	5.83 $\pm$ 0.10	6.55
4793.03 $\pm$ 0.25	0.18 $\pm$ 0.03	5.55 $\pm$ 0.09	6.03
5289.10 $\pm$ 0.33	0.47 $\pm$ 0.09	3.89 $\pm$ 0.11	3.81

Table 11. Beta branchings and $\log ft$ values for ^{91}Kr decay

^{91}Rb Levels (keV)	Percent Beta Branching	$\log ft$	$\log f_{1t}$
0.00 $\pm$ 0.00	10.00 $\pm$ 5.00	6.41 $\pm$ 0.22	8.39
108.78 $\pm$ 0.07	15.90 $\pm$ 3.03	6.18 $\pm$ 0.09	8.14
502.01 $\pm$ 0.09	0.68 $\pm$ 0.29	7.41 $\pm$ 0.18	9.32
506.56 $\pm$ 0.12	3.79 $\pm$ 1.28	6.67 $\pm$ 0.15	8.57
555.54 $\pm$ 0.09	0.98 $\pm$ 0.21	7.24 $\pm$ 0.10	9.13
662.41 $\pm$ 0.07	1.05 $\pm$ 0.12	7.17 $\pm$ 0.06	9.05
721.64 $\pm$ 0.14	0.59 $\pm$ 0.48	7.40 $\pm$ 0.36	9.27
1133.78 $\pm$ 0.13	1.64 $\pm$ 0.33	6.80 $\pm$ 0.09	8.60
1136.73 $\pm$ 0.17	1.30 $\pm$ 0.27	6.90 $\pm$ 0.10	8.70
1178.02 $\pm$ 0.09	0.66 $\pm$ 0.15	7.17 $\pm$ 0.10	8.97
1211.07 $\pm$ 0.17	0.32 $\pm$ 0.16	7.48 $\pm$ 0.22	9.27
1267.72 $\pm$ 0.14	1.59 $\pm$ 0.16	6.76 $\pm$ 0.05	8.54
1304.25 $\pm$ 0.13	0.46 $\pm$ 0.24	7.28 $\pm$ 0.22	9.06
1324.27 $\pm$ 0.12	0.77 $\pm$ 0.12	7.05 $\pm$ 0.07	8.83
1401.81 $\pm$ 0.18	0.84 $\pm$ 0.15	6.98 $\pm$ 0.08	8.74
1501.62 $\pm$ 0.11	2.94 $\pm$ 0.42	6.40 $\pm$ 0.07	8.14
1547.67 $\pm$ 0.18	1.19 $\pm$ 0.12	6.77 $\pm$ 0.05	7.75
1615.19 $\pm$ 0.08	6.17 $\pm$ 0.60	6.03 $\pm$ 0.05	8.50
1637.05 $\pm$ 0.15	0.55 $\pm$ 0.10	7.07 $\pm$ 0.08	8.79
1722.85 $\pm$ 0.15	0.89 $\pm$ 0.10	6.82 $\pm$ 0.06	8.53
1775.49 $\pm$ 0.13	0.66 $\pm$ 0.08	6.93 $\pm$ 0.06	8.62
1778.98 $\pm$ 0.18	0.38 $\pm$ 0.10	7.17 $\pm$ 0.12	8.86
1975.16 $\pm$ 0.15	1.11 $\pm$ 0.11	6.61 $\pm$ 0.05	8.27
2002.75 $\pm$ 0.14	0.14 $\pm$ 0.07	7.49 $\pm$ 0.21	9.14
2037.36 $\pm$ 0.17	< 0.08	> 7.81	9.45
2089.78 $\pm$ 0.18	2.75 $\pm$ 0.25	6.17 $\pm$ 0.05	7.80
2195.85 $\pm$ 0.20	0.87 $\pm$ 0.09	6.61 $\pm$ 0.06	8.22
2377.26 $\pm$ 0.17	0.54 $\pm$ 0.08	6.73 $\pm$ 0.07	8.30
2381.57 $\pm$ 0.30	0.81 $\pm$ 0.09	6.55 $\pm$ 0.06	8.13
2490.10 $\pm$ 0.18	2.98 $\pm$ 0.25	5.93 $\pm$ 0.05	7.48
2559.42 $\pm$ 0.18	1.64 $\pm$ 0.16	6.15 $\pm$ 0.05	7.69
2593.17 $\pm$ 0.09	4.60 $\pm$ 0.37	5.59 $\pm$ 0.05	7.21
2686.75 $\pm$ 0.22	0.67 $\pm$ 0.09	6.47 $\pm$ 0.07	7.98
2729.11 $\pm$ 0.20	0.69 $\pm$ 0.08	6.44 $\pm$ 0.06	7.93
2844.67 $\pm$ 0.14	2.55 $\pm$ 0.25	5.81 $\pm$ 0.05	7.27
2861.51 $\pm$ 0.18	3.92 $\pm$ 0.35	5.61 $\pm$ 0.05	7.07
2919.94 $\pm$ 0.20	2.04 $\pm$ 0.17	5.86 $\pm$ 0.05	7.31
2926.83 $\pm$ 0.26	0.27 $\pm$ 0.07	6.73 $\pm$ 0.12	8.17
2964.06 $\pm$ 0.17	1.37 $\pm$ 0.14	6.01 $\pm$ 0.06	7.44
2979.67 $\pm$ 0.33	1.68 $\pm$ 0.17	5.91 $\pm$ 0.06	7.34
3002.27 $\pm$ 0.18	3.16 $\pm$ 0.28	5.62 $\pm$ 0.05	7.05

Table 11. (Continued)

^{91}Rb Levels (keV)	Percent Beta Branching	$\text{Log} f_{\text{t}}$	$\text{Log} f_{\text{t}}$
3044.49 $\pm$ 0.19	0.37 $\pm$ 0.07	6.52 $\pm$ 0.09	7.94
3046.19 $\pm$ 0.22	0.36 $\pm$ 0.04	6.54 $\pm$ 0.06	7.96
3056.91 $\pm$ 0.19	1.47 $\pm$ 0.25	5.92 $\pm$ 0.08	7.33
3090.66 $\pm$ 0.23	2.38 $\pm$ 0.19	5.69 $\pm$ 0.05	7.09
3113.55 $\pm$ 0.12	3.29 $\pm$ 0.31	5.53 $\pm$ 0.05	6.93
3206.16 $\pm$ 0.17	0.76 $\pm$ 0.08	6.11 $\pm$ 0.06	7.49
3218.22 $\pm$ 0.22	< 0.18	> 6.72	8.09
3325.04 $\pm$ 0.23	0.66 $\pm$ 0.11	6.09 $\pm$ 0.08	7.44
3687.51 $\pm$ 0.46	0.34 $\pm$ 0.06	6.13 $\pm$ 0.09	7.36
3910.08 $\pm$ 0.24	0.75 $\pm$ 0.10	5.61 $\pm$ 0.07	6.77
3974.23 $\pm$ 0.23	0.20 $\pm$ 0.07	6.13 $\pm$ 0.17	7.27
4072.16 $\pm$ 0.26	0.12 $\pm$ 0.02	6.27 $\pm$ 0.10	7.37
4129.14 $\pm$ 0.23	0.73 $\pm$ 0.07	5.44 $\pm$ 0.06	6.52
4199.46 $\pm$ 0.32	0.19 $\pm$ 0.03	5.96 $\pm$ 0.09	7.01
4211.61 $\pm$ 0.27	0.56 $\pm$ 0.10	5.48 $\pm$ 0.09	6.53
4543.23 $\pm$ 0.24	0.58 $\pm$ 0.09	5.13 $\pm$ 0.08	6.03
4545.80 $\pm$ 0.40	0.26 $\pm$ 0.05	5.47 $\pm$ 0.09	6.37
4569.64 $\pm$ 0.50	0.37 $\pm$ 0.08	5.30 $\pm$ 0.18	6.19
4683.55 $\pm$ 0.27	0.57 $\pm$ 0.11	4.98 $\pm$ 0.10	5.81
4698.00 $\pm$ 0.23	0.81 $\pm$ 0.09	4.80 $\pm$ 0.07	5.63

F. 93.6- and 108.8-keV Level Half-lives

Only the first-excited states in both $A = 91$ nuclei studied were believed to be long-lived enough to be measured by the delayed-coincidence method.

Figure 15 shows the delayed-coincidence time spectrum, along with the fitted function, for the 93.6-keV transition to the ground state in ^{91}Sr where the time calibration is 0.8336 nsec/channel. The half-life for the level from which this transition originated was found to be 87.5 ± 3.0 nsec and agrees with previous measurements (14, 15, 16).

The ICC and multipolarity of the 93.6-keV transition determined in Section C were used to interpret the half-life of the 93.6-keV level. With this information, it was possible to find the enhancement of this transition to be 16.1 relative to the appropriate Weisskopf estimate (32). This value is well within the norm for E2 enhancement factors. If the effective nucleon charge were e , the E2 transition rate would be about 3 Weisskopf units. However, the enhancement factor shows the effective charge for the neutrons to be about $2.3e$ which is not an unreasonable value.

The 108.8-keV level half-life was too short to be properly determined by the fitting method. However, the centroid shift method (difference between $F(t)$ and $P(t)$) yields a value of approximately 1.5 nsec (consistent with most M1 transitions).

Figure 15. Delayed coincidence time spectrum and fitted function for the decay of the 93.6-keV level of ^{91}Sr

V. DISCUSSION

A. Shell-model States

In this chapter an attempt will be made to establish spin and parity assignments for the levels of the odd-A nuclei, ^{91}Sr and ^{91}Rb , and to interpret some of the levels in terms of the shell-model states available to the nucleons. ^{88}Sr is assumed to be a closed-shell nucleus (core) to which the extra particles (or holes) are attached. Relative to the core, the available proton states are the $2p_{3/2}$ and $1f_{5/2}$ proton-hole states and $2p_{1/2}$ and $1g_{9/2}$ proton-particle states. Neutrons above $N = 50$ may occupy the $2d_{5/2}$, $2d_{3/2}$, $3s_{1/2}$, and $1g_{7/2}$ states, all of which are positive-parity particle states.

According to the shell model, the dominant ground-state nucleon configurations for ^{91}Kr , ^{91}Rb , and ^{91}Sr should be:

$$^{91}\text{Kr}; \quad \pi(2p_{3/2})^{-2} \nu(2d_{5/2})^5,$$

$$^{91}\text{Rb}; \quad \pi(2p_{3/2})^{-1} \nu(2d_{5/2})^4,$$

$$\text{and } ^{91}\text{Sr}; \quad \nu(2d_{5/2})^3.$$

Thus, the decays from the ground states of ^{91}Kr to ^{91}Rb and from ^{91}Rb to ^{91}Sr are expected to involve the decays of $2d_{5/2}$ neutrons into $2p_{3/2}$ protons. The following discussion will show both nuclei to agree with these features to a large extent.

B. Discussion of the ^{91}Sr Level Scheme

Most of the low-lying states in ^{91}Sr are expected to involve the three neutrons beyond $N = 50$ in the available configurations. In approximate decreasing order of binding energy (and increasing order of excitation energy), the expected positive-parity configurations for three neutrons with seniority, $\underline{s}$, and spin, $\underline{J}$, ($J \leq 9/2$) are:

	$s=1$	$s=3$
$\nu(2d_{5/2})^3$	$J= 5/2$	$3/2, 9/2$
$\nu(2d_{5/2})^2(2d_{3/2})$	$J= 3/2$	$1/2, 3/2, 5/2, 7/2, 9/2$
$\nu(2d_{5/2})^2(3s_{1/2})$	$J= 1/2$	$3/2, 5/2, 7/2, 9/2$
$\nu(2d_{5/2})^2(1g_{7/2})$	$J= 7/2$	$1/2, 3/2, 5/2, 7/2, 9/2$

Other positive-parity configurations would involve more than one neutron outside the $2d_{5/2}$ subshell.

In terms of the predicted dominant shell-model configuration, the implied spin-parity assignment for the ground state of ^{91}Sr is $5/2^+$. This assignment is supported by the first-forbidden unique beta decay (33) to the $1/2^-$ ground state of ^{91}Y and the remaining beta decay (26) to the excited states. It is also consistent with the $\log ft$ value of 7.30 for the first-forbidden beta decay from the $3/2^-$ ground state of ^{91}Rb (to be discussed in Section C). Addi-

tional evidence for this assignment is provided by the systematics of other $N = 53$ nuclei (Ref. 34) as shown in Figure 16. The $\nu(2d_{5/2})^3$, $s=1$ configuration appears to be the dominant configuration for the ground state of each nucleus.

The systematics also suggest that the predominant configuration for the 93.6-keV level should be the $3/2^+$ member of the $\nu(2d_{5/2})^3$, $s=3$ configuration. This is supported by the likely first-forbidden beta decay ($\log ft = 6.74$) from ^{91}Rb . The observed E2 character for the $3/2^+$ to $5/2^+$ transition is consistent with the assignments for both states since, according to de Shalit and Talmi (35), no M1 transitions occur within a j^n configuration of identical nucleons.

The low-lying $\nu(2d_{5/2})^2(2d_{3/2})$ configuration probably provides a portion of the overall wave function for the first-excited state. Of course, a contribution from this configuration must not give a significant M1 component to the 93.6-keV transition, but could account for the greater part of the direct beta branching to this level.

A calculation which demonstrates that a low-lying $\nu(2d_{5/2})^3$ state is reasonable was performed by Talmi (36) and Vervier (37) for the three states of this $\nu(2d_{5/2})^3$ configuration in ^{93}Zr . In order to apply Talmi's (36) method to ^{91}Sr , knowledge of the 0^+ , 2^+ , and 4^+ states from the $\nu(2d_{5/2})^2$ configuration in ^{90}Sr is required. Mason and

Figure 16. Systematics of N=53 isotones

Johns (13) have performed this calculation for ^{91}Sr which predicts the $3/2^+$ level to reside at 25 keV and the $9/2^+$ level to be near 1230 keV. The calculated $3/2^+$ state is in crude agreement with the location for the first-excited state in ^{91}Sr . A $9/2^+$, $s=3$ member of this configuration would not be directly populated by beta decay from the $3/2^-$ ground state of ^{91}Rb . Although the 1368-keV level has a beta branch consistent with zero, likely to be the $9/2^+$ state, due to the presence of the 1274-keV transition to the first-excited $3/2^+$ state.

The $\nu(2d_{5/2})^2(2d_{3/2})$ configuration is expected to be the dominant configuration for the 439-keV level giving it a spin-parity assignment of $3/2^+$. The $\nu(2d_{5/2})^2(3s_{1/2})$ configuration is unlikely since the transition to the first-excited state would involve an orbital angular momentum change of two. The strength of the transition from the 439-keV level to the 93.6-keV level indicates the possibility that both states may be linear combinations of the two pure configurations $\nu(2d_{5/2})^3$, $s=3$ and $\nu(2d_{5/2})^2(2d_{3/2})$, $s=1$.

The remaining states below 2657 keV may well have spins from $1/2$ to $7/2$ with positive parity since they are, in all probability, populated by first-forbidden beta decay. No probable configuration assignments can be made for these states from the available information, but these states are

likely to involve the $s=3$ combinations of a pair of $2d_{5/2}$ neutrons and a neutron in either the $2d_{3/2}$, $3s_{1/2}$, or $1g_{7/2}$ subshell as well as combinations with only one $2d_{5/2}$ neutron.

Intense transitions to the first-excited state and absence of transitions to the ground state provide a weak argument for $1/2^-$ assignments to the 2657- and 3693-keV levels populated by allowed beta decay. The $1/2^-$ assignment is preferred over the $3/2^-$ or $5/2^-$ choices since, with a $1/2^-$ choice, the absence of ground-state transitions could be due to the lack of competition between E1 and M2 transitions. If the ground-state configuration of ^{91}Rb contained a small admixture from $\pi(2p_{3/2})^{-2}\nu(2d_{5/2})^2(1g_{7/2})^2$, $s=1$, then the configuration $\pi(2p_{3/2})^{-2}(1g_{5/2})\nu(2d_{5/2})^2(1g_{7/2})$, $s=1$ might describe these $1/2^-$ states. Only a few percent of such a configuration in the ^{91}Rb ground state would be sufficient to give the low $\log ft$ values obtained for these levels. The suggested configuration for the 2657-keV and 3693-keV levels, however, does not explain why the transitions from these levels to the first-excited states are much more intense than the other transitions from these levels.

Allowed beta decay to the 3737-, 4043-, 4157-, 4189-, and 4265-keV levels indicates that these states have negative parity with possible spins ranging from $1/2$ to $5/2$. This multitude of negative parity states is expected if con-

figurations like those proposed for the 2657-keV and 3693-keV states exist.

Since no reaction studies of ^{91}Sr have yet been reported, there is little supportive evidence for the speculations presented. Certainly, reaction studies with targets of ^{90}Sr are possible and once performed will yield valuable information pertaining to the levels of ^{91}Sr .

C. Discussion of the ^{91}Rb Level Scheme

The lowest-energy states in ^{91}Rb are expected to involve the proton-hole states below $Z = 38$ and the proton-particle states above $Z = 38$. Relative to the ^{88}Sr core and in approximate order of increasing excitation energy, the expected odd-parity configurations with seniority, s , and spin, J ($J \leq 9/2$) are:

	$s=1$	$s=3$
$\pi(2p_{3/2})^{-1}\nu(2d_{5/2})^4$	$J= 3/2$	$1/2, 3/2, 5/2, 7/2, 9/2$
$\pi(2f_{5/2})^{-1}\nu(2d_{5/2})^4$	$J= 5/2$	$1/2, 3/2, 5/2, 7/2, 9/2$
$\pi(2p_{3/2})^{-2}(2p_{1/2})\nu(2d_{5/2})^4$	$J= 1/2$	$3/2, 5/2, 7/2, 9/2$
$\pi(2f_{5/2})^{-2}(2p_{1/2})\nu(2d_{5/2})^4$	$J= 1/2$	$3/2, 5/2, 7/2, 9/2$

As mentioned in Section A, the ground state of ^{91}Rb is expected to be a $3/2^-$ state with its predominant configura-

tion being $\pi(2p_{3/2})^{-1}\nu(2d_{5/2})^4$. The observed beta decay to this level from the ground state of ^{91}Kr (expected $5/2^+$) has a $\log ft$ value of 6.41 which is consistent with a first-forbidden transition. The strongest evidence for the $3/2^-$ assignment comes from the systematics of Rb nuclei (Ref. 34) as shown in Figure 17.

An assignment of $5/2^-$ to the 108.8-keV level agrees with the measured M1 transition between the 108.8-keV state and the ground state. This assignment is also consistent with the beta branching to this level since the $\log ft$ of 6.18 is reasonable for a first-forbidden nonunique beta decay. If the first-excited state were purely from the $\pi(2f_{5/2})^{-1}\nu(2d_{5/2})^4$ configuration, a transition to the ground state would involve an orbital angular momentum change of two. However, de Shalit and Talmi (35) admit that such "L-forbidden" transitions have been observed. On the other hand, a minor admixture to this level from the $5/2^-$ member of the $\pi(2p_{3/2})^{-1}\nu(2d_{5/2})^4$, $s=3$ configuration could permit this transition to proceed with a relatively small hindrance factor.

Figure 17 shows that the $5/2^-$ and $1/2^-$ states draw progressively nearer to the $3/2^-$ state as N increases beyond 50. The $1/2^-$ state is probably created by promoting the unpaired $2p_{3/2}$ proton into the $\pi(2p_{3/2})^{-2}(2p_{1/2})\nu(2d_{5/2})$ configuration. The 502- and 662-keV levels are likely

Figure 17. Systematics of $Z=37$ isotopes

candidates for this low-lying $1/2^-$ state due to the strong transitions to the ground state and absence of transitions to the first-excited state.

States at 2593, 2845, 2862, 3002, and 3114 keV are probably $3/2^+$ or $5/2^+$ since they were populated by allowed beta decay. $7/2^+$ has been eliminated from these states because all have strong transitions to the ground state and M2 transitions are quite unlikely to compete with E1 transitions. Positive-parity states are probably due to the unpaired proton in the $1g_{9/2}$ subshell.

The remaining low-lying states and many of the intermediate states are probably negative parity as predicted by the systematics. Very few positive parity states are likely at low excitations. Due to the lack of adequate information and the large number of possible configurations, there is little use in additional speculation regarding the other states.

An examination of the ^{91}Rb level scheme through an "effective interaction" calculation was attempted. No specific information about the form of the two-body interaction was made, but the potential well determining the single nucleon wave functions was assumed to be uniform for all nucleons in this region.

Information about the two-body interaction between the $\pi(2p_{3/2})^{-1}$ and $\nu(2d_{5/2})$ configurations was taken from ^{88}Rb

which has four possible states (1-, 2-, 3-, and 4-) for coupling a proton hole to a neutron. Information for the two-body interaction between pairs of $2d_{5/2}$ neutrons was found in ^{92}Sr . The levels of interest in both nuclei are shown in Figure 18. The energies of these levels supply the parameters needed for the calculation. This calculation was made with no additional adjustable parameters.

Nine states were calculated as the 0^+ , 2^+ , and 4^+ states couple to the $\nu(2p_{3/2})^{-1}$, $s=1$ and $s=3$ configurations. Other configurations were not considered in the calculation, due to the lack of suitable information from neighboring nuclei. The results from this calculation are presented in Figure 19. Although overall agreement is poor, the clustering of the four intermediate states is very similar to the clustering of the intermediate experimental states in ^{91}Rb . The effective interaction technique seems to work better for nuclei with fewer nucleons to consider since the energy differences between shells and subshells is greater.

In conclusion, the structure of the ^{91}Rb nucleus is not well understood and requires more detailed study.

Figure 18. Low-lying levels in ^{88}Rb and ^{92}Sr

Figure 19. Experimental and calculated levels in ^{91}Rb

VI. APPENDIX A: EXPERIMENTAL NOTES

Table 12. Gamma-ray calibration standards¹

Nuclide	Gamma-ray energies (keV)
⁵⁶ Co	846.753, 1037.817, 1175.071, 1238.255, 1360.176, 1771.307, 1810.701, 1963.675, 2015.135, 2034.709, 2113.049, 2212.862, 2598.399, 3009.523, 3201.884, 3253.342, 3272.915, 3451.068, 3547.842
⁵⁷ Co	14.411, 122.063, 136.473
⁶⁰ Co	1173.210, 1332.475
¹³³ Ba	53.16, 79.62, 80.998, 160.60, 223.11, 276.397, 302.851, 356.005, 383.851
¹³⁷ Cs	661.643
¹⁸² Ta	31.736, 42.715, 67.750, 84.680, 100.105, 113.673, 116.418, 152.434, 156.387, 179.393, 198.356, 222.110, 229.322, 264.072, 1121.273, 1189.023, 1221.377, 1230.990, 1257.391, 1273.705, 1289.127, 1373.807, 1387.376
¹⁹² Ir	136.337, 295.950, 308.447, 316.498, 468.063, 484.571, 588.574, 604.403, 612.453, 884.525
²²⁶ Ra	186.14, 241.96, 295.20, 351.92, 609.27, 665.40, 768.35, 785.80, 806.16, 934.06, 1120.28, 1155.17, 1238.13, 1280.98, 1377.64, 1401.44, 1407.98, 1509.22, 1661.24, 1729.55, 1764.49, 1838.33, 1847.44, 2118.52, 2204.14, 2447.63

¹Calibration energies are weighted averages from those of Greenwood, et al. (38, 39, 40) and Multhauf and Tirsell (41). Intensities were adopted from reports by Gunnick, et al. (42), Camp and Meredith (43), Aubin, et al. (44), Henry (45), and Edwards, et al. (46).

VII. APPENDIX B: COMPUTER PROGRAMS

A. Description of Programs

1. Program PEAKFIND

The computer code PEAKFIND is used to make initial peak identification and provide preliminary fits on a raw singles spectrum. The program is patterned after a second difference method of Mariscotti (47) to find peaks. A detailed description of PEAKFIND is being prepared by Schick (48).

Several runs on the data with PEAKFIND allow preliminary adjustments to the linearization parameters for peak shape as functions of energy. Finally, PEAKFIND provides punched card output with initial estimates for use in the main peak fitting program, SKEWGAUS.

2. Program SKEWGAUS

SKEWGAUS is a peak fitting program developed to fit the peaks in multichannel analyzer spectra as obtained from semiconductor detectors. Since SKEWGAUS has been described in detail by Schick (49), only a brief outline of the program will be presented here.

The basic form of the fitting function is a Gaussian to which an exponential tail is smoothly joined on the low energy side of the peak. Additional parameters to handle upper and lower skewness and backscatter tail can be included when a better fit is desired.

For fitting purposes the fitting region is divided into three regions by SKEWGAUS. Region I contains an exponential tail, a backscatter tail, and a lower skewness term. Region II contains a pure Gaussian and a backscatter tail. Region III contains a pure Gaussian and an upper skewness term.

The complete fitting function may be written as follows:

Region I ($x < x_0 - \tau$):

$$f = h[(1-t) + a(-z-v)^N] \exp[v(v+2z)] + ht$$

Region II ($x_0 - \tau < x < x_0$):

$$f = h(1-t) \exp(-z^2) + ht$$

Region III ($x_0 < x$):

$$f = h(1+bz^M) \exp(-z^2)$$

where

$$z = (x-x_0)/(\sqrt{2} \sigma)$$

$$v = \tau/(\sqrt{2} \sigma)$$

$$\sigma = (\text{FWHM})/\sqrt{8 \ln 2}$$

Here x_0 is the location of the peak centroid, h is the peak height, FWHM is the full-width-at-half-maximum of the Gaussian, τ is the distance from the centroid to the crossover point, t is the ratio of tail height to peak height, a is the lower skewness parameter, and b is the upper skewness parameter. To this basic function a linear or quadratic background could be added.

Fitting is accomplished by applying a standard non-linear, least-squares fitting routine using Gauss's iteration method. Linearization parameters and punched output from PEAKFIND are input for SKEWGAUS. SKEWGAUS output provides peak centroids, heights, areas, and associated errors for use in program DRUDGE.

3. Program DRUDGE

DRUDGE transforms the peak centroids, heights, areas, and their associated errors into energies, intensities, and their associated errors. DRUDGE also assists in the identification of single-escape peaks, double-escape peaks, and Compton edges. Escape peaks are determined by comparing intensity ratios of single- or double-escape peaks to that of the photopeak. Compton edges are determined from energy considerations.

In addition to the punched output from SKEWGAUS, input to DRUDGE consists of internal calibration energies, system nonlinearity, a detector relative efficiency table, a table of relative attenuation due to absorbers, and tables of single- and double-escape peak intensity to photopeak intensity ratios.

DRUDGE output giving energies, intensities, and errors may be punched on cards for input to the level scheme construction program, LVLSURCH.

4. Program LVLSURCH

LVLSURCH is an energy-oriented iterative program used to extend decay schemes for which some levels are known, but where several unplaced transitions exist. For input, it needs a list of known level energies, transition energies and intensities (DRUDGE output), and (optionally) coincidence data.

Possible new levels are found by adding transition energies to known level energies. The program then determines all possible transitions between this possible level and all known levels. Limitations which can be applied to this operation are:

- 1) A predetermined number of transitions must enter or leave the possible level.
- 2) A tolerance in the closeness of a transition energy to the energy difference between two levels must be satisfied.
- 3) A transition entering or leaving this level must be consistent with the coincidence information.

These new levels are added to the list of known levels and another iteration begins to search for other possible new levels. Transitions may be fixed between two known levels so they will not be considered in the search for possible new levels.

5. Program TIMEFIT5

TIMEFIT5 is a five-parameter non-linear least-squares fitting program which calculates mean lives from delayed coincidence spectra. The program was initially developed by Morman, et al. (23) and recently modified by the present author.

TIMEFIT5 corrects for the tailing observed on the late side of the timing peak when a Ge(Li) detector is used for a stop signal. The background gate provides a prompt spectrum to be subtracted from the timing spectrum for the peak gate. Multiple backgrounds may be considered, a linear background may be subtracted from the prompt spectrum, and the fit may be performed over any number of designated channels.

The values of fit parameters, errors, fit matrix and error matrix are are printed after each iteration. A channel-by-channel listing of data and values of the fit function may be printed. Finally, a plot which includes the data and the final fit function will be output.

6. Auxiliary programs

The ICC program is a modification of the spline interpolation program of Hager and Seltzer (25) used to calculate partial or total internal-conversion coefficients at desired energies from the coefficients found in the Hager and Seltzer tables. Conversion coefficients from either pure or mixed transition types may be calculated.

LEAF is a program which uses the total internal-conversion coefficients calculated by ICC, transitions placements as determined by LVLSURCH, and the percent ground-state beta feeding (either assumed or measured). It compiles the information into a level scheme and calculates the best level energies from weighted averages and the percent beta feedings from intensity imbalances for all levels.

Punched output from LEAF is input to program LOGFT to calculate $\log ft$ values. The program calculates the Fermi function with either statistical or unique first-forbidden shape factors from the percent beta branchings. The program also allows compensation for atomic screening effects.

VIII. LITERATURE CITED

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IX. ACKNOWLEDGEMENTS

The author wishes to express his sincere thanks to many people for their assistance and encouragement leading to the completion of this project:

Dr. W. L. Talbert, Jr., who, as thesis advisor, suggested this topic for investigation and adroitly guided it to its completion. He is responsible for the inception and development of the TRISTAN facility which made this endeavor possible. His perception and knowledge of physics provided a stimulus for the accomplishment of this work.

Drs. F. K. Wohn, W. C. Schick, J. C. Hill, and S. A. Williams for many helpful discussions concerning experimental techniques, analysis of data, and interpretation of results.

J. R. McConnell, M. A. Cullison, D. R. Lekwa, and A. R. Landin (who were, at times, amusing) for their long hours of labor to make TRISTAN an exceptional facility and patience while instructing me in the operation of the system.

My colleagues, Drs. L. J. Alquist, J. F. Wright, and J. A. Morman, and Messrs. C. J. Bischof and W. R. Western, for experimental assistance and many helpful discussions.

S. M. Schoenung for many hours of proofreading.

Numerous other members of Group VII for their aid.

D. M. Reiter for his patient efforts while drawing the level schemes.

Edwin Bates for initiating my interest in physics as an undergraduate.

M. L. Gartner, who I slaughtered in chess, for raising my morale.

My parents, Mr. and Mrs. Malcolm Glascock, for their encouragement throughout my education.