GAMMA-RAY DECAY SCHEMES FOR ^{89}Kr
AND ^{89}Rb

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Gamma-ray decay schemes for ^{89}Kr and ^{89}Rb

by

Eugene Albert Henry

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Gamma-ray decay schemes for ^{89}Kr and ^{89}Rb

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A study of gamma-ray de-excitation following the beta decay of ^{89}Kr and ^{89}Rb produced by the TRISTAN on-line isotope separator is reported. Measurements of gamma-ray energies and intensities were made using Ge(Li) detectors. Level schemes have been constructed for ^{89}Rb and ^{89}Sr with the aid of gamma-gamma coincidence information, and beta branching was determined from equilibrium data and gamma-intensity balances. The excited levels of ^{89}Sr appear to be explained by single-particle states and the coupling of single-particle states to the vibration states of ^{88}Sr . The ^{89}Rb nucleus is shown to have a complex level scheme and will require further studies to clarify the picture of its nuclear structure.

1. INTRODUCTION

The study of radioactive gases and their daughters produced in the fission of uranium is an endeavor which is over thirty years old. In 1940 G. N. Glasoe and J. Steigman (1) collected the gases produced from uranium undergoing fission and were able to identify ^{89}Sr and ^{89}Rb and measure their half-lives. From their experiment they also inferred the presence of ^{89}Kr with a half-life of 1 to 5 minutes. Due to their nearness to the doubly closed shell nuclei ^{88}Sr and ^{90}Zr , much interest has continued to be shown in the $A = 89$ nuclei (Figure 1). The current work is an effort to improve and expand our knowledge of the $A = 89$ nuclei in an area that has previously been difficult to study, namely the decays of ^{89}Kr and ^{89}Rb .

The aim of studies of the nucleus is to deduce the exact nature of the nucleon-nucleon interaction. Over the years this knowledge has proved elusive indeed and nuclear scientists have resorted to various models to explain nuclear phenomena. These various models have enabled scientists to make reasonable predictions of nuclear structure within small regions of nuclei and to understand some aspects of the nucleon-nucleon interaction. Among the most successful of these models is the shell model of Mayer and Jensen which finds applicability near closed shell nuclei like ^{88}Sr and ^{90}Zr . In addition the eigenstates of the shell model often serve as a basis for more complex studies. Thus knowledge of the $A = 89$ nuclei can serve to improve our understanding of this important closed shell region.

Figure 1. A schematic drawing of the A = 89 nuclides available at TRISTAN

A. Fission and Beta Decay

Two important physical processes involved in the production of the radioactive nuclei studied in this research are fission and beta decay. Rare gases are produced in the thermal neutron induced fission of ^{235}U and by a series of beta decays the daughter activities are produced.

Fission is the process by which a heavy nucleus splits into two fragments with the emission of gamma rays, neutrons, and energy. Because the binding energy per nucleon decreases with increasing mass for A greater than about 50, all nuclei with A greater than 50 would like to undergo fission spontaneously. In fact only a few very heavy nuclei undergo spontaneous fission. The reason lies in the fission process itself.

A crude model for fission is the liquid drop model in which the nucleus starts in a spherical shape. When some energy is added to the nucleus, it may deform into a dumbbell shape and finally separate into two fragments. In each fragment the nucleons are more tightly bound than in the original nucleus. However in the intermediate dumbbell configuration, the nucleus undergoing fission has a much higher potential energy due to the increased average distance between nucleons which are strongly attracted to each other. As a result, though some nuclei such as ^{235}U have a certain small probability of undergoing spontaneous fission, energy must usually be supplied to overcome the potential barrier and cause a nucleus to undergo fission.

The energy necessary for fission to take place can be supplied by several methods including absorption of high energy gamma rays and neutron absorption. A neutron absorbed by a nucleus contributes not only the

kinetic energy it has, but also its binding energy as it becomes a part of the nucleus. For some nuclei the mere absorption of a neutron with no kinetic energy is sufficient to cross the fission threshold. For instance, when ^{235}U absorbs a thermal neutron, 6.4 MeV in binding energy is supplied to the new ^{236}U nucleus. However, since the critical energy for fission in ^{236}U is 5.3 MeV, the ^{236}U nucleus formed by the neutron capture undergoes fission immediately.

The types of nuclear fragments that result from fission vary with the parent nucleus and the energy of the fission inducing particle. It is unusual, however, for the nucleus undergoing fission to split symmetrically or exactly in half. For example the thermal neutron induced fission of ^{235}U is symmetric only once in 10^4 fissions (2). Generally the fission is asymmetric. In the thermal neutron fission of ^{235}U the fragment spectrum peaks near $A = 95$ and $A = 139$ and falls off quite rapidly on both sides of these maxima (3) (Figure 2). An average of about 2.4 prompt neutrons per fission is released in addition to the fragments.

Because the heavy nuclei are very rich in neutrons the fission fragments can lie quite far from the valley of beta stability. In order to obtain a more stable nuclear mix of protons and neutrons, the fragments emit one or more beta rays, converting the same number of neutrons to protons. The beta decay occurs over a period of time which is unique for each nuclear species. This time period is measured by the half-life, the time in which one-half of an original number of nuclei will have undergone beta decay.

The total amount of kinetic energy available in beta decay, Q_β , is

Figure 2. Yield curves for the thermal induced fission of ^{235}U as a function of A and Z

given by the difference between the ground state rest mass energies of the parent and the daughter nuclei (ignoring the ionization energy of the last atomic electron which is very small). This energy can appear as kinetic energy of the emitted electron, kinetic energy of the unobservable neutrino which always accompanies beta decay, or as excitation energy of the daughter nucleus. Because a neutrino is emitted from the nucleus along with the electron, the electrons appear with a continuum of energies up to the endpoint energy. If both the electron and neutrino appear with no kinetic energy, the total energy available for kinetic energy, Q_β , is deposited with the daughter nucleus. Thus the highest excitation energy observable in the daughter nucleus is determined by Q_β .

In general not all possible excited states of the daughter nucleus below Q_β will be observed. The excited states of the daughter populated by beta decay are determined by selection rules for total angular momentum and parity. The beta decay transitions are classified by these selection rules. A quantitative measure of the type of transition involved in a given decay is the log ft value. This number is proportional to the inverse square of matrix elements involving the initial and final nuclear states and the quantum mechanical operators. As can be seen the log ft value can be a useful indicator of the nature of states in the daughter excited by beta decay.

B. Previous Work and Historical Perspective

Historically, advances in the spectroscopy of radioactive nuclides have paralleled advances in technology. With the continued development of source preparation techniques, electronic systems, and detector systems,

nuclear science has pushed forward. The earliest investigations of mass 89 used absorption methods to study beta decay and the mere identification of members of the decay chain was a big step. The 1950's and early 1960's brought studies with scintillation detectors and primitive multichannel analyzers. The development of solid state detectors was a major advance making possible the observation of fine detail in a gamma ray spectrum. Early source preparation consisted of collecting the recoil fission fragments through a foil. Fast chromatography procedures were used extensively for studies of krypton and xenon decay chains in the 1960's. The present work uses mass separated sources and the latest in detector and electronic systems (see Chapter II) to continue the study of ^{89}Kr and ^{89}Rb decays. A review of previous work on mass 89 nuclides reveals the advances made in their study.

In one of the earliest studies, Seelman-Eggebert (4) (1940) collected radioactive rare gases produced in the fission of uranium and was able to identify a number of activities including kryptons, xenons, and their decay products. He was able to assign an observed 3-minute half-life to krypton, a 15.5-minute half-life to rubidium, and a 170-minute half-life to krypton plus rubidium.

At about the same time Hahn and Strassmann (5), and Glasoe and Steigman (1) correctly established some of the decay chains responsible for the gaseous fission product activity. In particular they assigned a short (about 3 minute) half-life to ^{89}Kr and a 15.4-minute half-life to ^{89}Rb . This chain they distinguished from the mass 88 chain where they assigned a 3-hour half-life to ^{88}Kr and a 17.8-minute half-life to ^{88}Rb .

Glasoe and Steigman also determined a 3.8-MeV endpoint energy for the ^{89}Rb decay using absorption techniques.

Bleuler and Züntli (6) (1946) reviewed extensively the endpoint energy determinations up to that time. They carefully investigated the various techniques used in endpoint energy determinations and, recalculating the results of Glasoe and Steigman, they reported a Q_β of 4.5 MeV for ^{89}Rb .

Because of the favorable distribution of half-lives among the krypton and rubidium fission products, a relatively pure source of ^{89}Rb can be easily prepared. In an early study, O'Kelley, Lazar, and Eichler (7) (1956) investigated the beta and gamma radiation of ^{89}Rb using the emanations from an enriched uranium fission source. The recoil krypton fission fragments were collected through an aluminum foil which absorbed the heavier xenon fission fragments. Later, chemical separation was used to improve the yield and purity of ^{89}Rb . Using scintillation detectors of NaI(Tl) crystals and a 20 channel pulse height analyzer, about 10 photo-peaks were observed. O'Kelley et al. also measured the Q_β to be 3.92 MeV and proposed a level scheme for ^{89}Sr based on their results.

Four gamma rays which were attributed to the nuclear decay of ^{89}Kr were reported by Prakash (8) (1960) in a study of fission products. The xenon fission product gases were selectively absorbed by activated charcoal from the emanant and the krypton activity was observed with a scintillation detector. On the basis of these gamma rays and some limited beta-ray information, a level scheme with five excited levels was proposed.

Wahlgren and Meinke (9) and Ockenden and Tomlinson (10) reported results of studies of a number of rare gas fission products (1962).

Wahlgren and Meinke irradiated samples of uranyl nitrate and, using rapid gas chromatographic separation methods developed by Koch and Grandy (11) and a NaI(Tl) counter, were able to observe gamma rays from the decay of ^{89}Kr . With a 100-channel pulse height analyzer approximately 20 gamma rays were identified. A Q_β of 4.6 MeV was obtained for the ^{89}Kr decay.

Ockenden and Tomlinson irradiated a uranium-235 stearate sample and using gas chromatography, a NaI(Tl) detector, and a 256-channel analyzer, were able to identify about 20 photopeaks as belonging to the decay of ^{89}Kr . Their results were in essential agreement with the work of Wahlgren and Meinke.

The advent of Ge(Li) detectors and highly emanating uranium compounds stimulated further investigation of short-lived fission products. Kitching and Johns (12,13) reported extensive studies of the decays of ^{89}Kr and ^{89}Rb as part of a systematic study of the krypton and rubidium isotopes at McMaster University.

These workers, using a source of ^{233}U deposited on hydrous zirconium oxide (which has a favorable yield of ^{89}Kr relative to ^{90}Kr and ^{91}Kr) and fast chromatography, obtained sources which were free of cesium contaminants and had 1 or 2% of ^{88}Rb and ^{90}Rb activities. These sources were studied using a 2 mm thick Ge(Li) detector, NaI(Tl) detectors, and a 512-channel pulse height analyzer. Some 15 photopeaks were detected and, with the aid of gamma-gamma and beta-gamma coincidence information, were placed in a level scheme for ^{89}Sr which had eight excited levels. They also obtained a value of 4.486 ± 0.012 MeV for Q_β for the ^{89}Rb decay using a magnetic spectrometer.

Kitching and Johns also reported comprehensive work on the decay of ^{89}Kr (1967). They used a variety of state-of-the-art Ge(Li) detectors, NaI(Tl) detectors for coincidence studies, and a 1024-channel analyzer. The sources were prepared using fast chromatography and had about 11% contamination from ^{87}Kr and ^{88}Kr . These workers reported a very complex gamma spectrum with more than 130 peaks. With the aid of gamma-gamma and beta-gamma coincidence information, the gamma rays were placed in a proposed level scheme for ^{89}Rb with 33 excited levels. A Q_β of 5.15 ± 0.03 MeV was reported for the ^{89}Kr decay with only about 0.1% beta feeding to the ground state of ^{89}Rb .

Little significant gamma spectroscopy has been done on ^{89}Kr or ^{89}Rb since the work reported by Kitching and Johns. However, Fiser and Kristak (14) (1970) reported about 35 gamma rays below 1700 keV from the decay of ^{89}Kr which were in essential agreement with those rays reported by Kitching and Johns. Fiser and Kristak measured the half-lives of five prominent photopeaks obtaining a half-life of 3.07 ± 0.08 minutes. They apparently had no knowledge of the previous work by Kitching and Johns. Bechemlil, LeMeur, and Poux (15) used a 25 cm^3 Ge(Li) detector and a 4000-channel analyzer in 1971 to observe a dozen strong photopeaks from the decay of ^{89}Rb and measured the half-lives of the 1032.2-keV and 1248.6-keV lines to be about 15.40 minutes. The gamma energies obtained by them are in somewhat better agreement with the present work than are those of Kitching and Johns.

Important contributions to the understanding of the ^{89}Sr level scheme have been made by experimenters using the $^{88}\text{Sr}(d,p)^{89}\text{Sr}$ reaction.

This reaction can excite single-particle neutron states and give information about their energies and spins. A large number of these studies (16-22) have been undertaken dating from 1951, the most significant of which have been by Preston, Sampson, and Martin (21) (1964) and by Cosman, Enge, and Sperduto (22) (1968). Preston et al. observed a close similarity between the energy levels of ^{89}Sr and ^{91}Zr . They noted that the states in ^{91}Zr appear somewhat higher in excitation energy than the corresponding states in ^{89}Sr . They attributed this result to neutron-proton interactions.

Cosman et al. reported some 36 excited levels below Q_β in their study of the $^{88}\text{Sr}(d,p)^{89}\text{Sr}$ reaction. Their results agreed well with previous reaction work as well as the work of Kitching and Johns. In addition to the single particle levels found, a large number of so called nonstripping levels were found. These transitions are characterized by angular distributions which are distinctly dissimilar to the generally more prominent stripping distributions. It was proposed that these levels could correspond to configurations in which neutron single-particle levels are coupled to low-lying 2^+ or 3^- states in the ^{88}Sr core.

Some emphasis has been placed recently on $^{88}\text{Sr}(p,p)$ and $^{88}\text{Sr}(p,p')$ reactions (23-25) as a means of studying the low-lying isobaric analogue states of ^{89}Sr . These reactions can be particularly helpful in the evaluation of state configurations which involve collective contributions. These configurations can involve a coupling of single-particle states to ^{88}Sr core excitations or single-particle states mixed by the presence of collective vibrations.

Up to the present time no study of ^{89}Rb using reaction methods has been reported in the literature.

C. Earliest Separator Efforts and Present Work

A study of ^{89}Kr and ^{89}Rb not discussed in the previous section but important in the context of the present work was that of Kofoed-Hansen and Nielsen (26,27) (1951). These experimenters were the first to use a mass separator for the study of mass 89 isotopes. Within a few seconds, high purity samples of a particular decay chain could be obtained for study. Values obtained for the half-lives of ^{89}Kr and ^{89}Rb were 3.18 minutes and 15.40 minutes, respectively, which are in good agreement with the most recent half-life measurements using separated sources (28).

This first study of mass separated $A = 89$ nuclei and other short-lived fission products was the early forerunner of many such present day experiments which demonstrate the power of this technique for observing short-lived activities. In the mid 1960's, an active interest developed in the use of isotope separator on-line (ISOL) facilities as a tool for studying nuclei far from the valley of beta stability (29-32). The TRISTAN system at the Ames Laboratory Research Reactor located at Iowa State University was the first ISOL system placed in operation at a reactor (33).

The present work uses the TRISTAN facility to produce high isotopic purity sources of $A = 89$ nuclides. The use of state-of-the-art Ge(Li) detectors and high-quality electronics enables a comprehensive study of the gamma spectra of ^{89}Kr and ^{89}Rb to be made.

II. EXPERIMENTAL ARRANGEMENT

Rare gas fission products are produced using thermal neutron induced fission of ^{235}U and made available for study by TRISTAN. Using a moving tape collector, particular members of a decay chain can be enhanced and observed with high resolution Ge(Li) detectors and electronic systems. Though portions of the facilities used in this experiment are discussed in detail in other publications (33-35), the entire experimental setup will be presented here because of its continual evolution.

A. The TRISTAN On-Line Isotope Separator System

A sample of uranium stearate containing 1.5 grams of ^{235}U is placed in an external neutron beam with a flux of 2×10^9 thermal neutrons per cm^2 per second at the Ames Laboratory Research Reactor. This sample serves as a source for fission gases for TRISTAN (Figure 3) and is placed in thin layers on a number of trays in the sample container to maximize emanation. A transport line of Teflon-lined neoprene tubing 1.7 meters long with a 1.27-centimeter inside diameter delivers the fission gases to the ionization chamber. The transport of the fission products is aided by a sweep gas of 98% helium and 1% each of krypton and xenon. This sweep gas, regulated by an automatic pressure controller, also serves to stabilize the ion source operating pressure which typically is 3 to 10 μTorr depending on sample and ion source conditions.

The ions are extracted from the ion source and accelerated through a potential which is normally 50 to 60 kilovolts. After passing through an electrostatic focusing section, the ions enter the separator magnet.

Figure 3. A block diagram of the TRISTAN facility

This 90-degree sector machine is of the Scandinavian type (36) and has a mean radius of 1.6 meters. The ion beams are brought to focus in the collector box and can be observed visually on a movable fluorescent screen near the focal plane. Dispersion at the focal plane is 1.8 centimeters between adjacent beams at mass 89. In the collector box, beam position stabilization is provided by monitoring a beam near the one under study. The ion beam being studied passes through a slit at the focal plane and the other beams are dumped in the collector box. The ion beam selected then passes between a pair of electrostatic deflection plates which enable the beam to be "turned off" at the detector positions when desired. Positive identification of the isobaric decay chain being selected for study is provided by a mass meter.

A switch magnet capable of a 45-degree deflection with secondary focusing properties provides a flexible switching system for TRISTAN. The ion beam can be delivered to five channels, three of which are now in use. Located at the two 45-degree channels, where the beams are well-focused, are the beta-ray spectrometer and the moving tape collector. A neutron detector is located at the 0-degree channel, where the beam is less well-focused.

A feature of the switch magnet is that it provides an added step of separation, reducing cross-contamination from adjacent masses. Contamination of activity due to mass A by activity due to masses $A \pm 1$ is normally less than 1 part in 5×10^5 at $A = 85$ (37). Additional contamination in the krypton mass region may be introduced, however, by KrH^+ complexes. The amount of contamination present from these complexes can

vary considerably depending on the fission sample and ion source operation conditions, but is usually small and easily dealt with.

A third source of contamination in this experiment is fission-produced bromine activities which are occasionally detected under optimum conditions. Detection of delayed neutrons indicates that about 2800 disintegrations per second of ^{89}Br can be obtained at the neutron detector channel with the present TRISTAN configuration (38). Since about 3% of the ^{89}Br nuclei decay with delayed neutron emission, additional mass 88 contaminations are introduced along with the ^{89}Br activity. However, the activity due to ^{89}Br is very small, about 1 part in 10^6 , and no gamma rays detected in this study are attributed to the decay of ^{89}Br .

The total transport time for krypton activities from the sample container to the detector systems is less than 2 seconds. This time does not include emanation time of the fission fragments from the uranium stearate. The transport time increases somewhat with ion source pressure, but little effect is found on yields of activities for isotopes with half-lives on the order of minutes.

The moving tape collector (Figure 4) currently in use is second generation with numerous capabilities. The ion beam is collected on 0.0025-centimeter thick aluminized Mylar tape which can be run continuously or in a stepped mode. In the continuous mode, the tape speed can be varied from about 0.025 to 5.0 centimeters per second. The stepped mode is controlled by the Daughter Analysis System control module which can be programmed for a number of collect, accumulation, and delay times (37). The tape collector has four gamma-detector ports, two each at the point of deposit (position #1) and at the daughter analysis point (position #2).

Figure 4. The moving tape collector used at TRISTAN

These ports normally have 0.16-centimeter thick aluminum windows. In a recent modification, one port at each position was fit with interchangeable windows, allowing for the installation of 0.005-centimeter thick Mylar windows when desired. Lead shielding is provided for the detector ports outside the tape collector.

An important feature of the moving tape collector is that the tape is electrically insulated from the housing, allowing a current pick-off to monitor the beam current. The ability to monitor the beam current at the point of deposit enables the separator and switch magnet to be tuned for maximum activity. Normally, preliminary tuning is done while monitoring an intense stable beam, such as ^{86}Kr , where about 1 microampere of beam current is available. Fine tuning is then done by selecting the beam desired for study and adjusting the separator and switch magnet for maximum current. Several nanoamperes of beam current are obtainable at mass 89.

B. Detectors

Ortec lithium-drifted germanium detectors were used in this experiment. Two are large volume, true-coaxial detectors and the third is a high resolution planar detector. The characteristics of these detectors are summarized in Table 1.

C. Electronic Systems

Two basic electronic systems were used in this study of the ^{89}Kr and ^{89}Rb decays. The circuitry (Figure 5) for gamma singles runs normally consisted of a large detector, an Ortec Model 120-28 preamplifier, a

Table 1. Detector characteristics

Detector Serial No.	10-637	10-684	GX-270
Geometry	True-Coaxial	True-Coaxial	Planar
Active Volume	57.3 cm ³	58.2 cm ³	1 cm ³
Resolution	2.3 keV at 1.33 MeV	2.3 keV at 1.33 MeV	650 eV at 122 keV
Efficiency	11.8%	9%	Not given
Peak-Compton Ratio	34:1	28:1	Not given
Absorbing Layers	0.5 mm Al 1.0 mm Teflon .64 cm plexiglass	0.5 mm Al 1.0 mm Teflon .64 cm plexiglass	0.13 mm Be ₂ 40.5 µg/cm ² Au

Tennelec Model TC203BLR linear amplifier, a 13-bit Geoscience Nuclear Model 8050 ADC, and a 16,384-channel modified TMC analyzer. Usually a Tennelec Model TC590 or a Hamner Model N-780A ratemeter was connected to one of the auxiliary amplifier outputs. A four µsec time constant, base-line restoration, and DC coupling between the main amplifier and the ADC typically produced the best system resolution and photopeak shape.

Constant fraction timing was used in the gamma-gamma coincidence circuit (Figure 6). The main components of this system include: Ortec Model 454 Timing Filter Amplifiers, Model 453 Constant Fraction Timing Discriminators, Model 427 Delay Amplifiers, and a Model 437 Time-to-Pulse-Height Converter; a Canberra Model 430 Single Channel Analyzer; Mech-Tronics Model 506 Delay Amplifiers; TMC Model 217A ADCs; the ALRR Format

Figure 5. The electronic circuitry used for singles measurements

Figure 6. The electronic system used for coincidence measurements

Selector and Buffer Tape System; and the 16,384-channel analyzer. Often, singles events were also recorded from one of the detectors.

A timing window of 40 nsec was used in the coincidence circuit. The use of a buffer tape system enabled all of the obtained coincidence information to be retained. With the use of the Format Selector and multi-channel analyzer, the experiment could be "played back" to look at as many different digitally-set coincidence gates as desired.

D. Data Accumulation

The moving tape collector was used in the continuous mode with a detector at position #1 to enhance ^{89}Kr activity. With a tape speed of 0.36 centimeters per second, the activity observed by the detector was primarily ^{89}Kr with the ^{89}Rb activity being carried away before much build-up occurred. Using ISOBAR (37), a computer program which calculates the activity of decay chain members for given tape collector settings, the integrated activity of each member could be obtained. Under the above condition, the integrated activity observed was 99.8% ^{89}Kr , 0.2% ^{89}Rb , and negligible ^{89}Sr .

The enhancement of ^{89}Rb activity was accomplished by using the stepped mode for the tape collector and placing a detector at position #2. Using this stepped mode, activity was collected at the point of deposit for 550 seconds. This activity, primarily ^{89}Kr , was allowed to decay for 750 seconds while the beam was deflected. Then the tape was stepped in about 10 seconds to position #2, and the accumulation of data continued for 1300 seconds. Simultaneously a new activity sample collection was started at position #1. Using ISOBAR, the integrated

activity obtained under these running conditions was 92.3% for ^{89}Rb , 7.6% for ^{89}Kr , and 0.3% for ^{89}Sr .

Using different tape collector running conditions, even greater enhancements of ^{89}Kr and ^{89}Rb are possible. Enhancement of ^{89}Kr can be improved by increasing the tape speed, while increasing the sample delay time at the point of deposit improves the ^{89}Rb enhancement. However, these further enhancements are made at the expense of total activity available for detection, making measurement times prohibitively long.

In addition to the two types of measurements discussed above, an equilibrium run has proven useful. For the equilibrium measurement only about 20% of the available beam was allowed to be deposited on the tape to prevent excessive activity build-up. After collecting activity for 2 hours, data accumulation was started and continued for 10 hours. True equilibrium was never reached because the continuously changing operating conditions of the separator system caused the amount of ^{89}Kr activity deposited to vary slightly with time. To overcome this problem, data were transferred to magnetic tape every 15 minutes. Preliminary analysis revealed which data sets had ^{89}Kr to ^{89}Rb ratios most nearly like those of the true equilibrium condition. These data sets were then used for final analysis of the equilibrium run.

Data in the analyzer memory from calibration or unknown sources could be made immediately available for preliminary analysis by using a Franklin Printer. All singles and coincidence gate data were also transferred to 7 track magnetic tape for use in later computer data analysis.

III. DATA ANALYSIS

Spectroscopic studies such as the ones undertaken at the TRISTAN facility can generate huge amounts of data. To cope with this inundation, a series of computer programs and data handling techniques have been developed by experimenters at TRISTAN which digest in a routine manner the raw data and perform subsequent calculations. An IBM 360/Model 65 computer processes the programs, while hand calculations that are still necessary are aided by a programmable Hewlett Packard Model 9100A calculator.

Four of the main computer programs used in the data analysis will be discussed in some detail in this chapter. These four programs are: PEAKFIND, which locates peaks and does preliminary fitting; SKEWGAUS, which is the main peak fitting program; DRUDGE, which uses calibration information to determine photopeak energies and intensities; and LASP, which aids in level scheme construction. Data handling techniques will be described where appropriate in the discussion of these programs. Auxiliary programs, coincidence data analysis, and error analysis will also be discussed briefly.

A. SKEWGAUS

Because the response functions of large Ge(Li) detectors and associated electronics are non-Gaussian, SKEWGAUS was developed to analyze gamma-ray spectra. This peak-fitting routine can handle both upper and lower skewness and a backscatter tail. For fitting purposes, each gamma ray is divided into three regions by SKEWGAUS (Figure 7). Region 1 contains

Figure 7. The SKEWGAUS fit function showing the three fit regions

an exponential decay, a backscatter tail (parameter A), and a skewness term (parameter B). Region 2 contains a pure Gaussian and a backscatter tail, while Region 3 contains a pure Gaussian and a skewness term (parameter C). Analytical expressions for the fit function in the three regions are:

Region	Function
1	$N_0(e^{-X_0(2X-X_0)}(1-A+B(X-X_0)^4) + A)$
2	$N_0(e^{-X^2}(1-A) + A)$
3	$N_0(e^{-X^2}(1+CX^5))$

In the fit function,

$$X = \frac{(E_p - E)}{\sqrt{2} \sigma}$$

where E_p is the energy of the centroid of the peak, σ is the Gaussian standard deviation, and E_0 , defined in terms of X_0 , is the "crossover energy", the boundary between the region of Gaussian behavior and the region of exponential decay. In practice, because it is more easily observable in the raw data, the full-width at half-maximum, FWHM, is the width parameter used in the program where $FWHM = \sqrt{8 \ln 2} \sigma$. Also in SKEWGAUS, the "crossover energy" is given by τ where $\tau = (E_p - E_0)$. Region 2 includes $E = E_0$ and $E = E_p$. Note that the term "energy" is used loosely in this discussion and the basic fit variable is channel number.

The above function is fit to the data with a nonlinear least-squares

fitting routine using Gauss's iteration method. SKEWGAUS can handle up to nine overlapping gamma rays in each fit, a feature which proves useful in analyzing complex spectra. A linear or quadratic background is fit simultaneously with the peaks by this program. Figure 8 shows the final SKEWGAUS fit for the 930 keV region in ^{89}Kr decay, demonstrating the versatility of this fitting routine.

FWHM and τ are linear functions of energy which are normally determined from analysis of isolated, intense photopeaks. Once these functions are determined, FWHM and τ are no longer allowed to vary freely but are determined for each fit from the linear functions. The lower skewness parameter, B, is less well defined and is usually found necessary only for very intense, low-energy peaks. The upper skewness parameter, C, is normally zero but may be necessary if high-side tailing appears (this may occur if count rates are high and no base-line restoration is used or if the amplifier pole zero is not properly adjusted). The backscatter tail parameter, A, is used only when analyzing spectra taken with silicon detectors.

B. PEAKFIND

PEAKFIND, developed after SKEWGAUS, is used to locate peaks in a spectrum and to make preliminary fits. This program uses the second difference method of M. A. Mariscotti (39) to find peaks. This method differentiates the peaks from a background with statistical fluctuations and, to a large extent, from Compton edges. Though the method as developed by Mariscotti assumed a Gaussian shape for the peaks, this method works well for skewed data from large Ge(Li) detectors because the

Figure 8. A SKEWGAUS fit of the 930-keV region of the ⁸⁹Kr spectrum

dominant portion of the peaks is still nearly Gaussian.

The peaks that are found by PEAKFIND are fit by it to the function used in SKEWGAUS with parameters A, B, and C set to zero. Preliminary adjustments to FWHM and τ as functions of energy are made by performing several runs on the data. Finally, PEAKFIND punches data which provides the initial estimates for the parameters for the fitting done by SKEWGAUS.

C. DRUDGE

The output of SKEWGAUS consists of peak centroids, areas, heights, and associated errors. DRUDGE transforms this information into energies and intensities, and provides additional information concerning underlying Compton edges and escape-related peaks. Three separate gamma-ray spectra are necessary to enable DRUDGE to properly calculate peak energies: a calibration source spectrum, an unknown source plus calibration source spectrum, and an unknown source spectrum. Calibration sources are normally chosen from among ^{60}Co , ^{207}Bi , ^{133}Ba , ^{56}Co , ^{57}Co , ^{241}Am , ^{152}Eu , ^{182}Ta , and ^{226}Ra to provide standards for both gamma-ray energy and intensity determinations. Detector relative efficiency tables, tables of relative attenuation due to absorbers, tables of intensity correction ratios, and tables of ratios of single- and double-escape peak intensities to photopeak intensities are also necessary for DRUDGE to determine peak intensities.

The energies of peaks in spectra obtained at the TRISTAN facility are very nearly a linear function of channel number. Small aberrations in the linear function are corrected by using the calibration spectrum to determine an integral nonlinearity (Figure 9), the difference between the

Figure 9. A typical integral nonlinearity curve from the ^{89}Kr experimental measurement

best straight line fit to the calibration data and the actual energies. This nonlinearity, ΔE , is fairly smooth and small, usually less than 0.5 keV except below 200 keV where it may rise rapidly to several keV. The integral nonlinearity is assumed not to vary for the three spectra taken for a given experiment. Using the calibration plus unknown spectrum then, the energies of intense, isolated photopeaks of the unknown activity are determined. Finally, using the energies of the unknown photopeaks determined from the calibration plus unknown spectrum, the energies of all other peaks in the unknown spectrum are determined.

The peak intensities are calculated by DRUDGE using the peak areas supplied by SKEWGAUS and folding in the detector relative efficiency, absorption, and intensity correction. The detector relative efficiency is determined from spectra where branching ratios or relative intensities are well known. The attenuation of gamma rays due to window thickness and absorbers was calculated using data from the National Bureau of Standards (40,41). An intensity correction is necessary because of three effects resulting from the use of a moving tape collector. The so-called collimator effect, in which activity on the tape moves behind the edge of a collimator, leads to a relative increase in the number of high energy photons reaching the detector compared to low energy photons which are absorbed by the collimator. Activity also builds up over a period of time on the tape take-up reel and high-energy photons have some probability of penetrating the shielding to the detector. In addition, when data are being accumulated at position #2 and activity is being collected at position #1, some high-energy photons from activity at position #1 can

penetrate to the detector. To correct for these effects, intensities for large, isolated photopeaks are determined from the equilibrium run where these effects do not occur, and a correction curve is obtained which can be determined for various moving tape settings. For ^{89}Kr decay, this energy-dependent correction varied by about a factor of 4 from the lowest energy to the highest energy gamma rays. In ^{89}Rb decay, the corresponding correction varied by about a factor of 1.5 (Figure 10).

A severe problem with the complex spectra in this study is the separation of single and double escape peaks from photopeaks. With SKEWGAUS, over 400 peaks were fit in the ^{89}Kr decay spectrum for a density of about 1 peak per 10 keV, resulting in many escape peak candidates. Careful construction of graphs of single-escape to photopeak and double-escape to photopeak intensity ratios enables escape peaks to be identified or appropriate corrections to be made. In this study, some calibration sources such as ^{56}Co and easily identifiable escape peaks from the unknown sources were used to determine these graphs. Errors were estimated for each point and an envelope drawn to serve as a guide in escape peak identification or in making intensity corrections (Figure 11). DRUDGE uses the data from this graph to compare intensity ratios of possible escape-peak/photopeak pairs and to indicate if they could be related. In this study, final determinations and corrections were made by hand. It was observed in the data analysis that escape peaks, especially single escape peaks, tended to be slightly wider than photopeaks in that energy region, which aided in escape peak identification.

The output from DRUDGE also indicates if a given peak could be

Figure 10. The intensity correction curve for the ^{89}Rb data

Figure 11. Escape-peak to photopeak intensity ratios

disturbed by an underlying Compton edge by simply calculating the Compton edge energy and comparing it directly to peak energies. The usefulness of this information has decreased now that detectors with high peak-to-Compton-edge ratios are in use at TRISTAN.

D. LASP

The basis for LASP is a level search program written by H. Levy (42). This program uses an efficient search method to locate possible new levels about known levels, between known levels, and below known levels. Possible new levels are grouped by energy for quick scanning. LASP is a modification which, in addition to the energy sum window of the original program, introduces a second criterion to test for new levels, namely the number of times the new level is found by the program. This second criterion can reduce dramatically the amount of extraneous output from the program and increase confidence in the new levels found. Options in the program allow new levels to be added to the list of established levels as the program executes.

E. Auxiliary Programs

Several auxiliary programs are used in data reduction. TRANSFER is used to transfer data from magnetic tape to private disk pack at the ISU Computation Center and to add a number of data sets together when necessary. UPLT is a flexible plotting routine which provides spectra graphs with smoothing if desired. SORT aids in selecting parent or daughter contaminants from an enhanced spectrum of the other. Gamma-ray energy lists from parent-enhanced and daughter-enhanced runs are checked for peaks

occurring at the same energy, and intensity ratios for these peaks are formed. Then parent-contaminant intensity ratios, for example, will all be renormalized to 1, while true daughter-peak intensity ratios will be some large number. Peaks which are attributable to both parent and daughter will have ratios somewhat larger than 1 though not as large as daughter peaks. LOGFT is used to calculate log ft values for energy levels once the percent beta feeding has been determined from gamma-ray population and depopulation. This program can include atomic screening corrections and first-forbidden unique beta spectrum shape in the log ft calculation if desired.

F. Coincidence Data Analysis

Using the ALRR Format Selector, all possible coincidence gates can be run from the obtained coincidence data. A background gate is also set just above each coincidence gate. Both the coincidence gate and the background gate spectra are transferred to magnetic tape and plotted using UPLT. The two plots are compared visually and valid coincidences are recorded. Coincidences are called definite if the height of the peak in question in the coincidence gate is statistically significant when compared to the same peak or region in the background gate. Coincidences are called possible if the height of the peak in question is not large enough when compared to background to call the coincidence definite, but some indication of peaking is seen. Coincidences are also called possible if the peak in question is seen but partially masked by other peaks or otherwise disturbed. As an example of the coincidence gate and background gate data used, plots of these gates, with coincidences

Identified, are shown for the 1248.10-keV photopeak in ^{89}Rb decay in Figure 12.

In practice, LASP output and coincidence gates are evaluated simultaneously during the construction of level schemes. LASP output points out possible coincidences to investigate and likewise, observed coincidences can suggest new levels to put into LASP. The absence of an intense photopeak in the total coincidence gate profile is also significant and can indicate that the photopeak depopulates to the ground state a level fed primarily by beta decay.

G. Error Analysis

A continual concern for the experimenter is error analysis. In studies of this type two aspects of error analysis are important: the meaningful assignment of errors to measured quantities, and sound error propagation. Errors must be assigned to the two basic resultant quantities, gamma-ray energies and intensities.

The determination of gamma-ray energy errors depends on the fitting of peaks in the spectrum, the extraction of errors in the fitting routine, and calibration. The uncertainties in the data in this study are presumed to be statistical and, following standard statistical methods, are given by $\sigma_i^2 = y_i$. The goodness of fit function,

$$\chi^2 = \sum_i w_i (y_i - f(y))^2$$

(where the summation is over all data points in the fit, i), depends on σ_i^2 through the weighting function, w_i , and on the difference between the

Figure 12. Background gate (below) and coincidence gate for spectra for the 1248.10-keV photopeak in the ^{89}Rb spectrum

data, y_i , and the fit function, $f(y)$. Following closely the result for a linear least-squares fit, it is reasonable to relate the uncertainty in each parameter for a nonlinear least-squares fit to the diagonal terms in the error matrix, $\underline{\epsilon}$ (the underscore denotes a matrix). Thus,

$$\sigma_{p_j}^2 = \epsilon_{jj}$$

where $\underline{\epsilon}$ is the inverse of the curvature matrix $\underline{\alpha}$ and p_j is the j^{th} fit parameter. In turn $\underline{\alpha}$ is given by

$$\alpha_{jk} = \frac{1}{2} \frac{\partial^2 \chi^2}{\partial p_j \partial p_k}.$$

Thus the parameter uncertainty is ultimately related to the data uncertainty and the difference between the data and the fit function, as well as first and second derivatives of the fit function.

In practice, calculation of second derivatives of the complex fit function used in SKEWGAUS is very difficult. As a result, $\underline{\alpha}$ is approximated by

$$\alpha_{jk} = \sum_i w_i \frac{\partial f(y)}{\partial p_j} \cdot \frac{\partial f(y)}{\partial p_k}.$$

In addition to its expediency, the dropping of the term involving second derivatives of $f(y)$ can be justified by noting that it is multiplied by the difference between the data and the fit function, $y_i - f(y)$. This difference is expected to fluctuate randomly both positive and negative and to cause the term involving second derivatives to be small on the average. Also taken into account in an empirical way is the differential

nonlinearity of the ADC, specified to be less than 0.5% by the manufacturer. This differential nonlinearity is folded into the weighting function which is then given by

$$w_i = (\sigma_i^2 + (0.005)^2 y_i)^{-1}.$$

The errors resulting from the above calculations seem reasonable in that the peaks which are intense, isolated and otherwise well-defined have small errors, while as intensity decreases or peak density increases, errors increase. An attempt to check the validity of energy errors was also carried out in the following way. To prevent overflows in the analyzer memory, data were transferred frequently to magnetic tape, resulting in a number of data sets for each experimental measurement. For one particular measurement, each data set was analyzed individually before the sets were summed. Then the total spectrum was analyzed. For several peaks the RMS average of the difference between the total spectrum peak position and the peak position in each data set was taken. This average difference was approximately equal to the error obtained by SKEWGAUS in the total spectrum. Thus, the method of error determination can be expected to give reasonable results for a single spectrum.

The calibration errors enter primarily in assigning errors to the integral nonlinearity curve (Figure 9). The errors for this curve were estimated from the errors given by the fit routine and the scatter in the calibration points. In the bootstrap region and the low-energy region, the errors are larger than in the well-calibrated region from

200 to 3500 keV.

DRUDGE converts the error in peak channel position to an energy error and combines it with the estimated error in the integral non-linearity using standard error propagation. In this determination, the error in the peak position is multiplied by 2, reflecting some of the approximations made in obtaining it.

In this calculation the errors in the gamma-ray energies of the calibration sources have not been taken explicitly into account. For all but a few calibration sources, the typical error quoted in energies is 50 eV. Some of this error may be implicit in the estimated integral nonlinearity curve errors. However, because of the uncertainty in the calibration sources themselves, no energies given in this study will have quoted errors less than 70 eV, even though for some isolated peaks the error calculated using the above procedures was as low as 30 eV.

Errors in gamma-ray intensity are derived from parameter uncertainties and uncertainties in the intensity correction curve (Figure 11) by DRUDGE. An additional 5% uncertainty term is included to compensate for the fact that no attempt is made to calculate the error introduced by the detector relative efficiency correction or the relative absorption correction. The resulting intensity errors are a minimum of 5%, which basically reflects the certainty with which the intensity of the most intense peak is known.

IV. DATA AND RESULTS

Using the data analysis methods described in the previous chapter, the gamma-ray spectra from the decays of ^{89}Kr and ^{89}Rb were analyzed. Over 400 peaks were observed in the ^{89}Kr spectrum and about 160 peaks were observed in the ^{89}Rb spectrum. Peaks from contaminant activities and background were identified and escape peaks were accounted for in each spectrum. Assignment of the remaining peaks was made to the appropriate decay. Finally, level schemes for ^{89}Sr and ^{89}Rb were constructed and the percent beta feeding and log ft values were calculated for each level.

A. Assignment of Photopeaks to ^{89}Kr and ^{89}Rb Decays

Since the use of the moving tape collector had quite effectively separated the ^{89}Kr and the ^{89}Rb activities, assignment of the bulk of the observed photopeaks to the proper decay was easily done. As will be seen later, the assignment of some of the gamma rays to both decays was important in the establishment of several energy levels in ^{89}Sr previously unobserved in gamma-ray studies. Of particular importance were the assignments of the 466-, 776-, 1472-, and 1939-keV gamma rays to both the ^{89}Kr and the ^{89}Rb decays.

The assignment of gamma rays of questionable origin was aided by the use of SORT (see Chapter III). Table 2 lists the gamma rays observed in both spectra, gives the renormalized intensity ratios from SORT for the ^{89}Rb spectrum (where the renormalized intensity ratios for the ^{89}Kr gamma rays should be 1), and gives the isotopic assignment. Many of the

Table 2. Isotopic assignment of photopeaks

Energy in ^{89}Kr Decay (keV)	Energy in ^{89}Rb Decay (keV)	Renormalized Intensity Ratio	Isotopic Assignment
205.03	205.74	10.51 ± 4.88	^{89}Kr and ^{89}Rb
220.90	220.54	1.00 ± 0.10	^{89}Kr
356.06	355.82	0.94 ± 0.18	^{89}Kr
466.13	466.62	8.99 ± 1.28	^{89}Kr and ^{89}Rb
576.96	576.89	0.91 ± 0.15	^{89}Kr
585.80	585.55	1.03 ± 0.11	^{89}Kr
657.81	657.71	4032 ± 458	^{89}Rb
696.24	696.20	1.20 ± 0.49	^{89}Kr
776.49	776.19	9.88 ± 1.47	^{89}Kr and ^{89}Rb
947.69	947.69	8551 ± 1282	^{89}Rb
1031.72	1031.88	8357 ± 813	^{89}Rb
1228.84	1228.40	84 ± 15	^{89}Kr and ^{89}Rb
1247.95	1248.10	7404 ± 743	^{89}Rb
1472.76	1473.22	6.17 ± 0.59	^{89}Kr and ^{89}Rb
1500.96	1501.07	15.23 ± 1.58	^{89}Kr and ^{89}Rb
1643.82	1644.15	8.60 ± 2.01	^{89}Kr and ^{89}Rb
1903.40	1903.49	1.46 ± 0.69	^{89}Kr
1939.11	1940.23	47 ± 6	^{89}Kr and ^{89}Rb
2007.11	2007.54	2206 ± 323	^{89}Rb
2195.76	2196.00	4334 ± 792	^{89}Kr and ^{89}Rb
2280.22	2280.06	87 ± 18	^{89}Kr and ^{89}Rb
2400.99	2400.94	0.87 ± 0.71	^{89}Kr
2707.83	2707.20	1603 ± 430	^{89}Rb
2946.89	2947.88	19.55 ± 4.80	^{89}Kr and ^{89}Rb
3140.26	3141.66	5.56 ± 0.77	^{89}Kr and ^{89}Rb

multiple assignments of photopeaks are confirmed by other information such as coincidence results. Note that the 2195.76-keV gamma ray is also assigned to the ^{89}Kr decay on the basis of a coincidence with the 585.80-keV gamma ray. Some intense photopeaks which are assigned solely to one decay or the other are included in Table 2 for comparison with the photopeaks assigned to both decays.

A number of peaks observed in each spectrum were of very low intensity. It was necessary to decide if these very low intensity peaks are real or result from statistical fluctuations in the background. In this experiment, only those peaks which had intensities which were at least twice their intensity uncertainty were retained as photopeak candidates. Exceptions were made for certain peaks which fit by energy sums between well-established levels in the level schemes. These exceptional gamma rays were required to have peak heights at least twice their peak height uncertainty.

B. The Construction of Level Schemes

The construction of level schemes for ^{89}Sr and ^{89}Rb began by establishing by inspection several excited levels involving the most intense gamma rays in each spectrum. These levels were easily confirmed by coincidence information and the energy sums involved were consistent to very good accuracy, often to 50 eV or less. For new excited levels to be established, a minimum of at least three gamma rays were required to be involved in the population and/or depopulation of the new levels to or from established levels. This requirement was relaxed only if additional information was available to confirm the new levels. This

additional information could be:

1. Coincidence confirmation.
2. The absence of an intense photopeak in the total coincidence profile, indicating that the photopeak depopulates to the ground state a level fed primarily by beta decay.
3. Energy sums involving a photopeak and an established level which put a new level above Q_{β} , indicating that the photopeak in question is a likely ground-state transition.
4. Reaction results indicating the presence of a level.

Because of the many gamma transitions and excited levels involved in these schemes, multiple placements of gamma rays by energy sums were sometimes possible. These multiple placements were made only when the coincidence information confirmed them. In other cases of possible multiple placement, where no coincidence information was available, preference was given to placement of the transition between well-established levels.

C. Percent Beta Branching Determination and Log ft's

Once the decay scheme for a nuclide is well known, the percent beta branching to the levels of the daughter can be determined, provided that the percent beta branching to at least one level of the daughter is known. Since the use of ISOBAR allows the integrated activities of each member of the decay chain being studied to be known relative to the other members of the chain, if just one beta branch in the entire chain is known and photopeaks from all members of the chain are seen, the beta branching from all the decays in the chain can, in principle, be obtained.

The one beta branch that must be known can be obtained from direct beta measurement or by some other means. In the absence of all beta branching knowledge, information from systematics may be helpful in estimating ground-state beta branching.

In a well-known decay scheme, the gamma-ray population and depopulation of a level indicates the amount of beta branching to that level relative to the other levels. Then once one beta branching ratio is determined for a given nucleus (usually the ground-state branching ratio), branching to all other levels can be found. Knowing the percent beta branching to each level, the log ft for that level can be calculated.

D. The ^{89}Rb Decay and the ^{89}Sr Level Scheme

Of the 62 gamma rays assigned to the decay of ^{89}Rb , 49 gamma rays or 79% are placed in the ^{89}Sr level scheme which has 16 excited levels. The 49 placed gamma rays account for 99.8% of the observed gamma-ray intensity. Figure 13 shows the ^{89}Rb spectrum with prominent peaks identified. Energies, relative intensities, intensities per 100 beta decays of ^{89}Rb , and placement in the ^{89}Sr level scheme are listed for the ^{89}Rb decay gamma rays in Table 3. As can be seen, of the 12 photopeaks which are attributed to both ^{89}Kr and ^{89}Rb , 10 are fit into the ^{89}Sr level scheme. For photopeaks that appear at the same energy as the escape peaks of higher energy gamma rays, appropriate intensity corrections are made. Apportionment of intensity for the 12 photopeaks observed in both decays was made with the aid of the percent integrated activities obtained for the enhanced measurements (see Chapter 11).

Figure 13. The ^{89}Rb decay spectrum

Figure 13. The ^{89}Rb decay spectrum (continued)

Figure 13. The ^{89}Rb decay spectrum (continued)

Figure 13. The ^{89}Rb decay spectrum. (continued)

Figure 13. The ^{89}Rb decay spectrum (continued).

Figure 13. The ^{89}Rb decay spectrum (continued)

Table 3. The photopeaks observed in ^{89}Rb decay

Energy (keV)	Relative Intensity ^a	Intensity (per 100 decays) ^b	Placement (keV)
118.29 $\pm$ 0.50	0.2 $\pm$ 0.1	0.01	2570 - 2451
205.74 $\pm$ 0.40	0.2 $\pm$ 0.1	0.01	3508 - 3303
272.45 $\pm$ 0.10	24.4 $\pm$ 1.2	1.6	2280 - 2007
289.76 $\pm$ 0.10	9.3 $\pm$ 0.5	0.59	2570 - 2280
466.62 $\pm$ 0.15	1.2 $\pm$ 0.3	0.073	1940 - 1473
562.50 $\pm$ 0.20	0.8 $\pm$ 0.1	0.05	2570 - 2007
595.96 $\pm$ 0.30	0.4 $\pm$ 0.1	0.03	3303 - 2707
657.71 $\pm$ 0.07	172 $\pm$ 9	10.9	3227 - 2570
699.62 $\pm$ 0.40	0.4 $\pm$ 0.1	0.03	2707 - 2007
766.79 $\pm$ 0.15	2.8 $\pm$ 0.3	0.18	2707 - 1940
776.19 $\pm$ 0.25	1.2 $\pm$ 0.3	0.073	3227 - 2451
801.08 $\pm$ 0.50	0.3 $\pm$ 0.2	0.02	3508 - 2707
822.03 $\pm$ 0.40	0.5 $\pm$ 0.2	0.03	4049 - 3227
947.69 $\pm$ 0.07	159 $\pm$ 8	10.1	3227 - 2280
975.32 $\pm$ 0.20	1.0 $\pm$ 0.2	0.062	2007 - 1031
1025.28 $\pm$ 0.50	3.9 $\pm$ 1.4	0.25	2058 - 1031
1031.88 $\pm$ 0.07	1000 $\pm$ 54	64.1	1031 - 0
1057.20 $\pm$ 0.40	0.4 $\pm$ 0.2	0.03	3508 - 2451
1081.43 $\pm$ 0.30	0.4 $\pm$ 0.1	0.03	3651 - 2570
1138.49 $\pm$ 0.50	0.2 $\pm$ 0.1	0.01	3845 - 2707
1160.47 $\pm$ 0.25	0.6 $\pm$ 0.1	0.04	
1211.70 $\pm$ 0.50	0.2 $\pm$ 0.1	0.01	
1220.32 $\pm$ 0.10	3.8 $\pm$ 0.3	0.24	3227 - 2007
1228.40 $\pm$ 0.15	2.1 $\pm$ 0.3	0.13	3508 - 2280
1234.02 $\pm$ 0.40	0.5 $\pm$ 0.3	0.03	2707 - 1473

^aMeasured relative to the 1031.88-keV transition.

^bCalculated from the decay scheme of Figure 16, and assuming a ground-state beta branch of 18%.

2

Table 3. (Continued)

Energy (keV)	Relative Intensity ^a	Intensity (per 100 decays) ^b	Placement (keV)
1248.10 ± 0.07	734 ± 39	46.7	2280 - 1031
1419.57 ± 0.10	1.6 ± 0.2	0.098	2451 - 1031
1429.62 ± 0.50	0.2 ± 0.1	0.01	
1473.22 ± 0.20	6.1 ± 0.5	0.38	1473 - 0
1501.07 ± 0.20	3.4 ± 0.3	0.21	3508 - 2007
1538.08 ± 0.10	44 ± 3	2.8	2570 - 1031
1596.15 ± 0.50	0.3 ± 0.1	0.02	
1644.15 ± 0.30	0.4 ± 0.1	0.03	3651 - 2007
1770.20 ± 0.80	0.2 ± 0.1	0.01	4049 - 2280
1940.23 ± 0.30	5.7 ± 0.4	0.36	1940 - 0
1979.74 ± 0.50	0.4 ± 0.1	0.03	3988 - 2007
2007.54 ± 0.10	41 ± 3	2.6	2007 - 0
2058.00 ± 1.10	4.0 ± 1.5	0.25	2058 - 0
2109.74 ± 0.50	0.3 ± 0.1	0.02	4049 - 1940
2196.00 ± 0.15	230 ± 15	15.2	3227 - 1031
2231.29 ± 0.40	0.4 ± 0.1	0.03	
2280.06 ± 0.10	3.1 ± 0.3	0.20	2280 - 0
2372.77 ± 0.90	0.2 ± 0.1	0.01	3845 - 1473
2451.90 ± 0.20	0.9 ± 0.1	0.06	2451 - 0
2570.14 ± 0.10	170 ± 9	10.8	2570 - 0
2668.03 ± 0.50	0.2 ± 0.1	0.01	
2685.55 ± 0.40	0.5 ± 0.1	0.03	
2707.20 ± 0.10	35 ± 2	2.3	2707 - 0
2818.10 ± 0.50	0.2 ± 0.1	0.01	
2947.88 ± 0.40	0.3 ± 0.1	0.02	
2955.02 ± 1.20	0.1 ± 0.05	0.006	3988 - 1031
3037.49 ± 0.40	0.2 ± 0.1	0.01	
3141.66 ± 0.30	0.9 ± 0.1	0.06	

Table 3. (Continued)

Energy (keV)	Relative Intensity ^a	Intensity (per 100 decays) ^b	Placement (keV)
3227.88 $\pm$ 0.15	1.3 $\pm$ 0.1	0.083	3227 - 0
3263.63 $\pm$ 0.30	0.3 $\pm$ 0.1	0.02	
3303.54 $\pm$ 0.80	0.1 $\pm$ 0.05	0.006	3303 - 0
3508.84 $\pm$ 0.25	19.8 $\pm$ 1.2	1.3	3508 - 0
3651.75 $\pm$ 0.40	0.6 $\pm$ 0.2	0.04	3651 - 0
3781.80 $\pm$ 0.50	0.2 $\pm$ 0.1	0.01	
3845.35 $\pm$ 0.60	0.5 $\pm$ 0.1	0.03	3845 - 0
3989.10 $\pm$ 0.80	0.3 $\pm$ 0.1	0.02	3988 - 0
4093.70 $\pm$ 0.60	1.3 $\pm$ 0.2	0.083	4093 - 0

Indicative (but fortunately not typical) of the problems faced in making intensity corrections is the problem of the 2196-keV peak which appears in both decays. At this energy appear the 2195.76-keV photopeak and 3219.84-keV double-escape peak from the ^{89}Kr decay, the 2196.00-keV photopeak and 2707.20-keV single-escape peak from the ^{89}Rb decay, and the 2196.10-keV photopeak from the ^{88}Kr contamination activity. The corrections made necessary by so many superimposed peaks reduce the relative intensity of the 2196.00-keV photopeak in ^{89}Rb decay from the apparent 242 to about 230.

Coincidence information from 13 coincidence gates on the ^{89}Rb spectrum are given in Table 4. Note that "possible" coincidences, as defined in Chapter III, are shown in parentheses. The level scheme for ^{89}Sr is

Table 4. ^{89}Rb coincidence information

Gate (keV)	Observed Coincidences (keV)
272	947, 975, 2007
289	657, 1031, 1248
657	289, 1031, 1248, 1538, 2570
947	272, 1031, 1248, 2007, 2280
1031	289, 657, 947, (1025), 1248, 1538, 2196
1248	289, 947, 1031, 1228
1473	(466), (766), (1234)
1501	2007
1538	657, 1031
1940	766
2007	272, (562), 947, 1220, 1501
2196	1031
2570	657

shown in Figure 14. The transition energy and intensity per 100 beta decays identify each placed gamma ray on the level scheme drawing. A solid circle at the head or tail of the gamma ray transition arrow indicates that "definite" coincidence information is available for the placement of that transition, while an open circle indicates "possible" coincidence relationship.

The major excited levels of ^{89}Sr (involving most of the intensity) have been reported in the spectroscopic study of ^{89}Rb decay by Kitching and Johns (12). These levels, at 1031.88, 2007.54, 2280.01, 2570.14, 2707.20, 3227.98, and 3508.81 keV in this work, are well established by energy sums and gamma-gamma coincidence information. The 2770-keV level reported by Kitching and Johns is not established in this work. The lowest four major excited levels can be identified with the 1031-, 2000-,

Figure 14. The ^{89}Sr level scheme

2266-, and 2558-keV levels found in the $^{88}\text{Sr}(d,p)^{89}\text{Sr}$ reaction studies of Cosman et al. (22). However, no reaction levels are found to correspond with the highest three major excited levels.

The energy levels observed for the first time by spectroscopy at 2451.9, 3303.5, 3651.7, 3845.7, 3988.1, 4049.2, and 4093.7 keV are based on energy sums. The level at 4093.7 keV is established because the gamma ray which depopulates that level could not populate the 1031.88-keV level without exceeding Q_β . The other six levels involve at least three transitions to or from other well-established levels.

The original search for the excited levels at 1473.22, 1940.23, and 2058.0 keV was inspired by the report of the levels in reaction data and the observation of gamma rays (namely the 466.62-, 766.79-, 1025.28-, 1473.22-, 1940.23-, and 2058.00-keV gamma rays) in the ^{89}Rb spectrum which fit a level scheme including these levels. The 2058.0-keV level is supported by the coincidence observed between the 1025.28- and 1031.88-keV photopeaks. This coincidence was extracted by carefully subtracting the background gate from the coincidence gate. A definite peaking was observed at 1025 keV. The coincidence is called "possible" because the weak 1025.28-keV photopeak lies in the tail of the extremely intense 1031.88-keV photopeak which could not be completely subtracted out. The 2058.0-keV ground state transition was found by carefully fitting the region of the single-escape peak of the 2570.14-keV photopeak.

The 1940.23-keV level is based on a definite coincidence of the 1940.23-keV photopeak and the 766.79-keV photopeak. The low-intensity 2109.74-keV gamma ray also populates this level from above. This level

is further supported by the 466.62-keV transition to the 1473.22-keV level.

Possible coincidences between the 466.62-, 766.79-, and 1234.02-keV gamma rays and the 1473.22-keV gamma ray are the basis for the 1473.22-keV level in ^{89}Sr . It can be seen in the ^{89}Kr decay scheme that the 1472.76-keV gamma ray is in coincidence with both the 220.90- and the 466.13-keV gamma rays. In the ^{89}Rb coincidence gate on the 1473.22-keV photopeak, coincidences are also seen with the 220.90- and the 466.62-keV gamma rays. However, the 1473.22- and 466.62-keV coincidence to 1473.22- and 220.90-keV coincidence intensity ratio is about 30 times larger in the ^{89}Rb gate than the 1472.76- and 466.13-keV coincidence to 1472.76- and 220.90-keV coincidence intensity ratio in the ^{89}Kr gate. Thus the 1473.22- and 220.90-keV coincidence in the ^{89}Rb gate is attributed to ^{89}Kr contamination activity while the 1473.22- and 466.62-keV coincidence is attributed mostly to ^{89}Rb activity. The 1473.22- and 466.62-keV coincidence in ^{89}Rb decay is called possible because of the difficulty of apportioning the amount of coincidence strength to each decay. The 766.79- and 1473.22-keV coincidence is seen through the 466.62-keV transition. An outside check on the validity of the 1473.22-keV level is provided by the coincidence between the 1473.22- and 1234.02-keV transitions.

E. Beta Branching from ^{89}Rb Decay and Log ft's

The beta branching from the decay of ^{89}Sr to levels in ^{89}Y has been measured (43,44) and could possibly be used to determine the beta branching from ^{89}Rb decay. Unfortunately, the ^{89}Sr beta decay branches

99.9985% to the ground state of ^{89}Y . This fact, combined with the 52 day half-life of ^{89}Sr , means that the 909.1-keV gamma ray of ^{89}Y , which depopulates the level populated by the 0.0015% beta branch, would be of very low intensity. Indeed, no gamma ray was seen at 909.1 keV in the ^{89}Rb decay spectrum. As a result, direct measurements of the ground state beta branch from ^{89}Rb have to be relied on.

Measurements of the ground-state beta branch from ^{89}Rb have been done by O'Kelley et al. (7) and Kitching and Johns (12). A ground-state beta branch of $7 \pm 5\%$ was obtained by O'Kelley et al. using a scintillation spectrometer. Kitching and Johns used a magnetic spectrometer with beta-gamma coincidence to establish that the beta group feeding the ^{89}Sr ground state accounted for 18% of the total beta decays of ^{89}Rb . This 18% ground-state beta branch is used in this work, along with gamma-ray population and depopulation intensities, to calculate the beta feeding of the other excited levels in ^{89}Sr .

The Q_β value of 4.486 ± 0.012 MeV measured by Kitching and Johns, also using the magnetic spectrometer, is used in this work for log ft calculations. In the log ft determination, a statistical shape is assumed for the beta spectrum shape and atomic screening is used. Table 5 lists the excited levels in ^{89}Sr , giving the percent beta feeding to each level and the associated log ft value.

F. The ^{89}Kr Decay and the ^{89}Rb Level Scheme

From the complex gamma-ray spectrum of ^{89}Kr decay, 299 photopeaks are assigned to ^{89}Kr decay, of which 260 or 86.7% are placed in a level scheme for ^{89}Rb with 53 excited levels. The placement of 260 gamma rays

Table 5. Percent beta branching and log ft's for ^{89}Rb decay

^{89}Sr Levels (keV)	Beta Group Energy (MeV)	Percent Beta Branching	Log ft
0.0	4.49	18 ^a	7.6
1031.88	3.45	~ 0	---
1473.22	3.01	0.25	8.7
1940.23	2.55	0.23	8.4
2007.54	2.48	0.48	8.0
2058.0	2.43	0.49	8.0
2280.0	2.21	37.2	6.0
2451.7	2.03	0.148	8.2
2570.14	1.92	3.25	6.8
2707.20	1.78	2.45	6.8
3227.9	1.26	36.2	5.0
3303.5	1.18	0.25	8.0
3508.8	0.98	1.67	6.0
3651.7	0.83	0.10	6.9
3845.7	0.64	0.05	6.8
3988.1	0.50	0.056	6.4
4049.2	0.44	0.06	6.1
4093.7	0.39	0.083	5.8

^aFrom Kitching and Johns (12).

accounts for 98.8% of the observed gamma-ray intensity. In Figure 15, the ^{89}Kr decay spectrum is shown with prominent peaks identified. Of special note are the doublets at 196.24 and 197.46 keV and 497.51 and 498.60 keV, which are indicated by peak broadening and the doublet at 1530.04 and 1533.68 keV, which is nearly completely resolved. These doublets have been previously unreported, and their identification aids in the establishment of several new levels. Table 6 lists energies, relative intensities, intensities per 100 beta decays of ^{89}Kr , and placement in the ^{89}Rb level scheme for the ^{89}Kr decay gamma rays. Again, as in the ^{89}Rb decay, appropriate intensity corrections were made where necessary. Of the 12 gamma rays assigned to both decays, all are placed in the ^{89}Rb level scheme.

A measurement was made with the Ge(Li) planar X-ray spectrometer, with the thin Mylar window in place on the moving tape collector, in an attempt to observe low-energy gamma rays and ^{89}Rb and ^{89}Kr X rays. No indication of low-energy gamma rays was seen and an upper limit of about 20 (out of 1000) was placed on the relative intensity of gamma rays that may be present from 8 to 197 keV. Also no X rays were seen in the 14- to 15-keV X-ray region of ^{89}Kr and ^{89}Rb , indicating that internal conversion does not occur with appreciable intensity in these two decays. The extremely low efficiency of the X-ray spectrometer, about 1%, limited the statistics of the measurement and made it impossible to rule out completely low-intensity gamma rays or ^{89}Kr and ^{89}Rb X rays.

Table 7 gives the information for the 105 coincidence gates from ^{89}Kr decay which were studied, with definite and possible coincidences

Figure 15. The ^{89}Kr decay spectrum

Figure 15. The ^{89}Kr decay spectrum (continued)

Figure 15. The ^{89}Kr decay spectrum. (continued)

Figure 15. The ^{89}Kr decay spectrum (continued)

Figure 15. The ^{89}Kr decay spectrum (continued)

Figure 15. The ^{89}Kr decay spectrum (continued)

Figure 15. The ^{89}Kr decay spectrum (continued)

Figure 15. The ^{89}Kr decay spectrum (continued).

Table 6. The photopeaks observed in ^{89}Kr decay

Energy (keV)	Relative Intensity ^a	Intensity (per 100 decays) ^b	Placement (keV)
196.24 $\pm$ 0.50	10.6 $\pm$ 5.4	0.24	1195 - 997
197.46 $\pm$ 0.30	91.0 $\pm$ 7.0	2.1	2598 - 2400
205.03 $\pm$ 0.20	6.2 $\pm$ 1.2	0.14	1693 - 1488
220.90 $\pm$ 0.07	1000 $\pm$ 56	22.5	220 - 0
242.20 $\pm$ 1.10	0.6 $\pm$ 0.4	0.01	2400 - 2160
264.11 $\pm$ 0.10	33 $\pm$ 2	0.74	1195 - 930
267.67 $\pm$ 0.30	4.2 $\pm$ 0.9	0.094	2866 - 2598
286.27 $\pm$ 0.40	1.3 $\pm$ 0.4	0.029	4367 - 4080
295.52 $\pm$ 0.70	0.8 $\pm$ 0.6	0.02	2160 - 1864
304.66 $\pm$ 0.70	1.1 $\pm$ 0.6	0.025	1998 - 1693
318.31 $\pm$ 0.30	2.2 $\pm$ 0.7	0.049	4367 - 4048
338.20 $\pm$ 0.10	17.1 $\pm$ 1.4	0.39	2160 - 1821
345.03 $\pm$ 0.10	59 $\pm$ 4	1.3	930 - 585
356.06 $\pm$ 0.07	207 $\pm$ 11	4.7	576 - 220
364.88 $\pm$ 0.10	45 $\pm$ 3	1.0	585 - 220
369.30 $\pm$ 0.10	69 $\pm$ 4	1.6	1693 - 1324
380.66 $\pm$ 0.30	2.3 $\pm$ 0.6	0.052	2781 - 2400
402.25 $\pm$ 0.20	15.9 $\pm$ 1.8	0.036	2400 - 1998
411.42 $\pm$ 0.10	128 $\pm$ 7	2.9	997 - 585
419.20 $\pm$ 0.30	1.9 $\pm$ 0.5	0.043	3017 - 2598
438.08 $\pm$ 0.10	48 $\pm$ 3	1.1	2598 - 2160
466.13 $\pm$ 0.10	40 $\pm$ 3	0.90	2160 - 1693
488.46 $\pm$ 0.60	3.9 $\pm$ 1.7	0.088	4631 - 4143
490.76 $\pm$ 0.20	16.1 $\pm$ 2.1	0.36	1488 - 997
497.51 $\pm$ 0.30	332 $\pm$ 27	7.5	497 - 0
498.60 $\pm$ 0.40	57 $\pm$ 10	1.3	1693 - 1195
523.53 $\pm$ 0.40	1.7 $\pm$ 0.6	0.038	2387 - 1864
542.19 $\pm$ 0.50	1.5 $\pm$ 0.6	0.034	4685 - 4143
546.93 $\pm$ 0.50	1.5 $\pm$ 0.6	0.034	4080 - 3532
557.30 $\pm$ 0.20	8.0 $\pm$ 0.8	0.18	1488 - 930
576.96 $\pm$ 0.10	282 $\pm$ 16	6.3	576 - 0
585.80 $\pm$ 0.07	826 $\pm$ 45	18.6	585 - 0
599.52 $\pm$ 0.20	4.4 $\pm$ 0.6	0.099	2598 - 1998
610.17 $\pm$ 0.70	0.9 $\pm$ 0.5	0.02	1195 - 585
626.20 $\pm$ 0.10	30 $\pm$ 2	0.68	1821 - 1195
629.75 $\pm$ 0.20	17.1 $\pm$ 1.3	0.39	2160 - 1530
652.60 $\pm$ 0.50	1.9 $\pm$ 0.7	0.043	3250 - 2598

^aMeasured relative to the 220.90-keV transition.^bCalculated from the decay scheme of Figure 14, a ^{89}Rb and ^{89}Kr equilibrium measurement, and assuming a ground-state beta branch of 18% for ^{89}Rb .

Table 6. (Continued)

Energy (keV)	Relative Intensity ^a	Intensity (per 100 decays) ^b	Placement (keV)
660.53 ± 0.60	2.4 ± 0.8	0.054	
662.86 ± 0.40	3.9 ± 0.9	0.088	1530 - 867
665.72 ± 0.20	5.7 ± 0.8	0.13	4631 - 3965
668.61 ± 0.60	2.1 ± 0.7	0.047	1864 - 1195
671.40 ± 0.20	5.3 ± 1.0	0.12	2365 - 1693
674.11 ± 0.20	11.6 ± 1.1	0.26	1998 - 1324
687.31 ± 0.40	3.5 ± 0.9	0.079	4048 - 3361
696.24 ± 0.10	89 ± 6	2.0	1693 - 997
707.01 ± 0.20	24.9 ± 1.7	0.56	2400 - 1693
710.05 ± 0.20	39 ± 3	0.88	930 - 220
729.63 ± 0.20	14.8 ± 1.6	0.33	3327 - 2598
738.39 ± 0.07	210 ± 11	4.7	1324 - 585
747.39 ± 0.30	5.7 ± 1.3	0.13	1324 - 576
753.54 ± 0.40	4.6 ± 1.2	0.10	1339 - 585
762.87 ± 0.30	20.0 ± 4.0	0.45	1339 - 576
	46 ± 6	1.0	1693 - 930
776.49 ± 0.20	56 ± 9	1.3	997 - 220
783.47 ± 0.90	1.1 ± 0.7	0.025	2781 - 1998
826.75 ± 0.10	38 ± 3	0.86	1324 - 487
835.53 ± 0.10	55 ± 4	1.2	2160 - 1324
857.37 ± 0.15	14.3 ± 1.2	0.32	3017 - 2160
867.08 ± 0.07	296 ± 15	6.7	867 - 0
870.42 ± 0.20	8.0 ± 0.9	0.18	2400 - 1530
904.27 ± 0.07	359 ± 20	8.1	2598 - 1693
917.78 ± 0.20	3.7 ± 0.6	0.083	2781 - 1864
930.95 ± 0.10	31 ± 2	0.70	930 - 0
934.61 ± 0.50	1.9 ± 0.6	0.043	1864 - 930
939.44 ± 0.30	3.3 ± 0.7	0.074	4405 - 3465
944.19 ± 0.15	8.2 ± 0.8	0.18	1530 - 585
953.18 ± 0.20	5.3 ± 0.8	0.12	1530 - 576
960.42 ± 0.10	16.1 ± 1.3	0.36	3361 - 2400
964.15 ± 0.40	2.9 ± 0.7	0.065	2160 - 1195
969.73 ± 0.30	4.7 ± 0.7	0.11	3370 - 2400
974.39 ± 0.10	49 ± 3	1.1	1195 - 220
997.37 ± 0.10	33 ± 2	0.74	997 - 0
1010.84 ± 0.20	5.4 ± 0.7	0.12	4338 - 3327
1038.28 ± 0.50	1.5 ± 0.6	0.034	
1044.40 ± 0.10	20.4 ± 1.4	0.46	2866 - 1821
1048.23 ± 0.30	3.1 ± 0.6	0.070	2387 - 1339
1058.62 ± 0.80	1.5 ± 0.8	0.034	3327 - 2269
1063.05 ± 0.40	3.5 ± 0.8	0.079	2387 - 1324
1067.74 ± 0.40	3.4 ± 0.8	0.076	1998 - 930
1076.48 ± 0.20	11.8 ± 1.3	0.27	2400 - 1324

Table 6. (Continued)

Energy (keV)	Relative Intensity ^a	Intensity (per 100 decays) ^b	Placement (keV)
1088.07 ± 0.10	17.9 ± 1.6	0.40	2781 - 1693
1098.06 ± 0.50	3.2 ± 1.2	0.072	4631 - 3532
1103.18 ± 0.20	45 ± 3	1.0	1324 - 220
1107.78 ± 0.10	146 ± 9	3.3	1693 - 585
1116.61 ± 0.07	83 ± 5	1.9	1693 - 576
1131.51 ± 0.20	8.0 ± 1.1	0.18	1998 - 867
1152.24 ± 0.40	3.2 ± 0.8	0.072	3017 - 1864
1162.50 ± 0.10	10.7 ± 1.0	0.24	2160 - 997
1167.41 ± 0.60	1.7 ± 0.7	0.038	3327 - 2160
1172.33 ± 0.20	49 ± 4	1.1	2866 - 1693
1182.38 ± 0.20	8.3 ± 1.1	0.19	4048 - 2866
1186.54 ± 0.20	9.2 ± 0.9	0.21	3327 - 2140
1195.14 ± 0.30	4.2 ± 0.7	0.094	1195 - 0
1200.59 ± 1.10	0.9 ± 0.6	0.02	3361 - 2160
1210.24 ± 0.90	1.1 ± 0.7	0.025	3370 - 2160
1228.84 ± 0.30	7.2 ± 0.9	0.16	2160 - 930
1235.62 ± 0.10	29.7 ± 2.3	0.67	1821 - 585
1241.51 ± 0.40	4.4 ± 0.8	0.099	
1251.00 ± 0.70	1.9 ± 0.8	0.043	2781 - 1530
1267.16 ± 0.60	1.2 ± 0.9	0.027	1488 - 220
1273.73 ± 0.10	68 ± 4	1.5	2598 - 1324
1278.50 ± 0.80	1.6 ± 0.9	0.036	1864 - 585
1298.01 ± 0.50	2.2 ± 0.7	0.049	4080 - 2781
1302.65 ± 0.30	5.0 ± 0.7	0.11	4631 - 3327
1308.90 ± 0.30	3.4 ± 0.7	0.076	1530 - 220
1324.28 ± 0.07	153 ± 9	3.4	1324 - 0
1335.39 ± 0.30	6.6 ± 1.3	0.15	2866 - 1530
1340.63 ± 0.30	9.7 ± 1.2	0.22	1339 - 0
1367.48 ± 0.20	7.4 ± 0.9	0.17	1864 - 497
1372.16 ± 0.20	6.3 ± 0.8	0.14	3370 - 1998
1381.91 ± 0.50	2.9 ± 0.8	0.065	4631 - 3250
1412.59 ± 0.15	13.2 ± 1.1	0.30	1998 - 585
1421.64 ± 0.20	11.2 ± 1.0	0.25	1998 - 576
1441.25 ± 0.80	1.0 ± 0.5	0.022	4307 - 2866
1455.31 ± 0.70	2.6 ± 1.1	0.058	
1458.32 ± 0.70	3.7 ± 1.2	0.083	2781 - 1324
1461.28 ± 0.50	6.1 ± 1.2	0.14	4478 - 3017
1464.24 ± 0.30	8.9 ± 1.2	0.20	2788 - 1324
1468.52 ± 0.30	9.4 ± 1.3	0.21	4487 - 3017
1472.76 ± 0.10	344 ± 19	7.7	1693 - 220
1481.92 ± 0.60	2.2 ± 1.0	0.049	4080 - 2598
1488.13 ± 0.40	4.7 ± 1.0	0.11	1488 - 0

Table 6. (Continued)

Energy (keV)	Relative Intensity ^a	Intensity (per 100 decays) ^b	Placement (keV)
1500.96 ± 0.10	66 ± 5	1.5	1998 - 497
1506.15 ± 0.30	5.6 ± 1.0	0.13	3327 - 1821
1530.04 ± 0.15	166 ± 10	3.7	1530 - 0
1533.68 ± 0.15	256 ± 14	5.8	2400 - 867
1555.28 ± 0.20	7.6 ± 0.9	0.17	2140 - 585
1573.78 ± 0.20	9.5 ± 0.9	0.21	2160 - 585
1582.87 ± 0.30	4.5 ± 0.7	0.10	2160 - 576
1600.71 ± 0.30	3.6 ± 0.7	0.081	1821 - 220
1634.06 ± 0.10	41 ± 3	0.92	3327 - 1693
1643.82 ± 0.10	16.9 ± 1.3	0.38	1864 - 220
1657.63 ± 0.50	2.0 ± 0.6	0.045	
1667.51 ± 0.20	6.4 ± 0.7	0.14	3361 - 1693
1676.91 ± 0.30	7.0 ± 1.1	0.16	3370 - 1693
1680.26 ± 0.50	4.2 ± 1.0	0.094	4080 - 2400
1683.82 ± 0.40	6.6 ± 1.2	0.15	2269 - 585
1692.00 ± 1.20	12.8 ± 5.1	0.29	3017 - 1324
1693.70 ± 0.10	219 ± 14	4.9	1693 - 0
1707.92 ± 0.80	1.2 ± 0.5	0.027	3977 - 2269
1710.70 ± 0.60	1.7 ± 0.6	0.038	3532 - 1821
1721.29 ± 0.15	11.2 ± 0.9	0.25	2218 - 497
1729.92 ± 0.60	1.5 ± 0.6	0.034	
1735.50 ± 0.40	2.8 ± 0.6	0.063	
1766.10 ± 0.40	2.4 ± 0.6	0.054	4631 - 2866
1777.60 ± 0.10	38 ± 3	0.86	1998 - 220
1788.24 ± 0.30	5.3 ± 0.8	0.12	2365 - 576
1791.35 ± 0.60	2.3 ± 0.7	0.052	2788 - 997
1804.41 ± 0.60	1.5 ± 0.6	0.034	
1810.73 ± 0.20	7.0 ± 0.8	0.16	2387 - 576
1823.61 ± 0.40	3.3 ± 0.7	0.074	2400 - 576
1827.30 ± 0.40	3.2 ± 0.6	0.072	
1831.30 ± 0.30	4.3 ± 0.6	0.097	3361 - 1530
1837.47 ± 0.40	5.9 ± 1.4	0.13	
1839.72 ± 0.25	17.5 ± 1.7	0.39	3327 - 1488
1850.57 ± 0.40	2.5 ± 0.6	0.056	2781 - 930
1865.24 ± 0.50	4.0 ± 0.7	0.090	1864 - 0
1868.47 ± 0.25	9.8 ± 0.9	0.22	2866 - 997
1879.80 ± 0.25	7.9 ± 0.8	0.18	4478 - 2598
1886.50 ± 0.60	1.7 ± 0.6	0.038	
1897.83 ± 0.70	1.5 ± 0.6	0.034	3719 - 1821
1903.40 ± 0.10	52 ± 5	1.2	2400 - 497
1925.31 ± 0.90	0.8 ± 0.6	0.02	3250 - 1324
1935.11 ± 0.60	1.7 ± 0.6	0.038	2866 - 930

Table 6. (Continued)

Energy (keV)	Relative Intensity ^a	Intensity (per 100 decays) ^b	Placement (keV)
1939.11 ± 0.15	32 ± 2	0.72	2160 - 220
1966.55 ± 0.20	6.6 ± 0.7	0.15	4367 - 2400
1977.70 ± 0.50	1.9 ± 0.6	0.043	3465 - 1488
1998.63 ± 0.50	5.9 ± 1.1	0.13	1998 - 0
2001.63 ± 0.90	1.8 ± 0.8	0.040	3532 - 1530
2012.23 ± 0.10	78 ± 5	1.8	2598 - 585
2021.04 ± 0.15	12.2 ± 1.0	0.27	2598 - 576
2039.48 ± 1.00	0.9 ± 0.5	0.02	4405 - 2365
2046.47 ± 0.15	13.1 ± 1.0	0.30	3370 - 1324
2079.29 ± 0.90	1.5 ± 0.6	0.034	
2082.47 ± 0.50	2.9 ± 0.7	0.065	4080 - 1998
2100.63 ± 0.08	47 ± 3	1.1	2598 - 497
2140.47 ± 0.60	3.1 ± 0.6	0.070	2140 - 0
2143.83 ± 0.40	3.2 ± 0.6	0.072	3965 - 1821
2150.11 ± 0.80	1.0 ± 0.6	0.022	3017 - 867
2160.02 ± 0.09	26.4 ± 1.8	0.59	2160 - 0
2167.90 ± 0.60	2.1 ± 0.7	0.047	
2189.98 ± 0.90	1.3 ± 0.7	0.029	3719 - 1530
2195.76 ± 0.40	6.4 ± 2.7	0.14	2781 - 585
2207.17 ± 0.50	2.3 ± 0.7	0.052	4367 - 2160
2232.55 ± 0.80	1.2 ± 0.5	0.027	4230 - 1998
2280.22 ± 0.30	10.2 ± 2.0	0.23	2866 - 585
2285.59 ± 0.80	2.3 ± 1.0	0.052	4685 - 2400
2321.65 ± 0.50	2.6 ± 0.7	0.058	4143 - 1821
2329.99 ± 0.80	1.8 ± 0.7	0.040	3327 - 997
2377.38 ± 0.90	40 ± 3	0.90	2598 - 220
2400.99 ± 0.09	36 ± 3	0.81	2400 - 0
2440.91 ± 0.40	2.3 ± 0.8	0.052	3017 - 576
2467.30 ± 1.10	0.8 ± 0.5	0.02	3465 - 997
2487.82 ± 0.80	1.2 ± 0.5	0.027	4631 - 2140
2503.02 ± 0.50	2.5 ± 0.6	0.056	3370 - 867
2522.03 ± 0.50	2.5 ± 0.6	0.056	3717 - 1195
2534.94 ± 0.30	4.7 ± 0.7	0.11	3532 - 997
2545.44 ± 0.60	2.5 ± 0.7	0.056	4367 - 1821
2549.85 ± 0.90	1.5 ± 0.6	0.034	4080 - 1530
2555.27 ± 0.80	1.7 ± 0.6	0.038	
2597.92 ± 0.20	5.4 ± 0.8	0.12	2598 - 0
2622.82 ± 1.00	1.1 ± 0.6	0.025	4487 - 1864
2645.26 ± 0.15	21.0 ± 1.5	0.47	2866 - 220
2659.08 ± 0.50	4.3 ± 0.8	0.097	
2703.23 ± 0.90	1.7 ± 0.7	0.038	
2721.91 ± 0.70	1.8 ± 0.7	0.040	3721 - 997
2742.33 ± 0.80	1.4 ± 0.6	0.031	3327 - 585

Table 6. (Continued)

Energy (keV)	Relative Intensity ^a	Intensity (per 100 decays) ^b	Placement (keV)
2750.92 $\pm$ 0.30	6.2 $\pm$ 0.7	0.14	3327 - 576
2756.60 $\pm$ 0.50	3.3 $\pm$ 0.7	0.074	4080 - 1324
2760.27 $\pm$ 0.70	2.3 $\pm$ 0.8	0.052	
2775.74 $\pm$ 1.10	1.5 $\pm$ 1.0	0.034	3361 - 585
2782.11 $\pm$ 0.10	38 $\pm$ 3	0.86	2781 - 0
2789.18 $\pm$ 0.60	2.6 $\pm$ 0.9	0.058	2788 - 0
2793.75 $\pm$ 0.20	34 $\pm$ 2	0.77	3370 - 576
2804.13 $\pm$ 0.80	2.0 $\pm$ 0.8	0.045	
2819.58 $\pm$ 0.25	6.6 $\pm$ 0.8	0.15	4143 - 1324
2853.25 $\pm$ 0.30	12.0 $\pm$ 1.7	0.27	3719 - 867
2866.23 $\pm$ 0.10	87 $\pm$ 5	2.0	2866 - 0
2873.79 $\pm$ 0.40	4.8 $\pm$ 0.9	0.11	3370 - 497
2878.69 $\pm$ 0.25	16.2 $\pm$ 1.5	0.36	3465 - 585
2917.37 $\pm$ 0.70	1.5 $\pm$ 0.5	0.034	4405 - 1488
2946.89 $\pm$ 0.40	3.9 $\pm$ 0.7	0.088	3532 - 585
2998.40 $\pm$ 0.60	2.2 $\pm$ 0.6	0.049	4487 - 1488
3017.92 $\pm$ 0.30	12.7 $\pm$ 1.4	0.29	3017 - 0
3029.16 $\pm$ 0.25	13.5 $\pm$ 1.2	0.30	3250 - 220
3049.72 $\pm$ 0.70	2.0 $\pm$ 0.6	0.045	
3098.75 $\pm$ 0.70	1.9 $\pm$ 0.6	0.043	3965 - 867
3107.26 $\pm$ 0.25	9.7 $\pm$ 0.9	0.22	3327 - 220
3140.26 $\pm$ 0.20	52 $\pm$ 4	1.2	3717 - 576
3154.36 $\pm$ 1.00	1.3 $\pm$ 0.7	0.029	4478 - 1324
3159.84 $\pm$ 0.60	3.1 $\pm$ 0.6	0.070	
3172.09 $\pm$ 0.30	5.0 $\pm$ 0.7	0.11	4367 - 1195
3213.24 $\pm$ 0.90	1.6 $\pm$ 0.6	0.036	4143 - 930
3219.84 $\pm$ 0.20	21.4 $\pm$ 1.6	0.48	3717 - 497
3257.02 $\pm$ 0.50	2.6 $\pm$ 0.6	0.058	3834 - 576
3271.30 $\pm$ 0.50	2.7 $\pm$ 0.6	0.061	
3300.01 $\pm$ 0.60	1.9 $\pm$ 0.6	0.043	4230 - 930
3317.86 $\pm$ 0.60	4.1 $\pm$ 0.9	0.092	
3321.93 $\pm$ 0.50	3.5 $\pm$ 0.8	0.079	3898 - 576
3340.82 $\pm$ 0.90	1.8 $\pm$ 0.7	0.040	4338 - 997
3347.44 $\pm$ 0.60	3.4 $\pm$ 0.8	0.076	
3351.94 $\pm$ 0.90	2.1 $\pm$ 0.7	0.047	
3361.70 $\pm$ 0.20	52 $\pm$ 4	1.2	3361 - 0
3371.12 $\pm$ 0.35	31 $\pm$ 3	0.70	3370 - 0
3399.88 $\pm$ 0.30	6.8 $\pm$ 0.7	0.15	3977 - 576
3439.57 $\pm$ 0.60	2.2 $\pm$ 0.6	0.049	4307 - 867
3463.26 $\pm$ 1.20	2.1 $\pm$ 1.2	0.047	4048 - 585
3503.60 $\pm$ 1.40	1.0 $\pm$ 0.6	0.022	4080 - 576
3532.88 $\pm$ 0.20	67 $\pm$ 4	1.5	3532 - 0

Table 6. (Continued)

Energy (keV)	Relative Intensity ^a	Intensity (per 100 decays) ^b	Placement (keV)
3567.91 ± 0.70	2.8 ± 0.9	0.063	
3583.90 ± 0.30	12.9 ± 1.0	0.29	4080 - 497
3629.22 ± 0.50	4.0 ± 0.7	0.090	
3634.39 ± 0.90	1.9 ± 0.6	0.043	4631 - 997
3639.05 ± 0.80	1.9 ± 0.6	0.043	4216 - 576
3652.34 ± 0.50	2.9 ± 0.6	0.065	
3665.40 ± 0.40	4.2 ± 0.6	0.094	
3677.74 ± 0.40	3.3 ± 0.6	0.074	3898 - 220
3717.76 ± 0.40	42 ± 3	0.94	3717 - 0
3721.45 ± 0.90	2.4 ± 1.0	0.054	4307 - 585
3732.51 ± 0.60	6.9 ± 2.5	0.16	4230 - 497
3756.54 ± 1.30	0.8 ± 0.5	0.02	3977 - 220
3781.43 ± 0.40	6.6 ± 0.6	0.15	4367 - 585
3809.51 ± 0.80	1.0 ± 0.4	0.022	4307 - 497
3827.42 ± 0.40	6.9 ± 0.8	0.16	4048 - 220
3837.57 ± 0.50	4.1 ± 0.5	0.092	
3842.73 ± 0.40	5.5 ± 0.6	0.12	4340 - 497
3882.48 ± 0.60	2.0 ± 0.4	0.045	
3898.42 ± 1.00	1.7 ± 0.9	0.038	3898 - 0
3901.66 ± 0.40	6.7 ± 1.0	0.15	4487 - 585
3923.02 ± 0.40	20.7 ± 1.4	0.47	4143 - 220
3965.53 ± 0.40	10.4 ± 0.8	0.23	3965 - 0
3977.54 ± 0.40	3.5 ± 0.6	0.079	4198 - 220
	13.5 ± 2.5	0.30	3977 - 0
3995.96 ± 0.40	7.1 ± 0.6	0.16	4216 - 220
4004.88 ± 0.70	1.4 ± 0.4	0.031	
4043.75 ± 1.00	1.0 ± 0.4	0.022	4631 - 585
4048.04 ± 0.50	5.8 ± 0.6	0.13	4048 - 0
4081.42 ± 0.50	3.7 ± 0.5	0.083	4080 - 0
4117.67 ± 1.10	0.7 ± 0.3	0.02	4338 - 220
4142.98 ± 1.20	1.3 ± 0.4	0.029	4143 - 0
4146.88 ± 1.30	0.8 ± 0.4	0.02	4367 - 220
4162.61 ± 0.60	1.4 ± 0.3	0.031	
4176.20 ± 1.10	0.6 ± 0.3	0.01	
4184.27 ± 0.60	2.5 ± 0.4	0.056	4405 - 220
4253.28 ± 1.00	0.7 ± 0.3	0.02	
4267.70 ± 0.60	1.4 ± 0.3	0.031	4487 - 220
4279.36 ± 0.70	1.0 ± 0.3	0.022	
4307.36 ± 1.10	0.5 ± 0.3	0.01	4307 - 0
4321.23 ± 1.10	0.5 ± 0.2	0.01	
4341.13 ± 0.60	5.2 ± 0.5	0.12	4340 - 0
4368.36 ± 0.75	2.1 ± 0.3	0.047	4367 - 0

Table 6. (Continued)

Energy (keV)	Relative Intensity ^a	Intensity (per 100 decays) ^b	Placement (keV)
4405.08 ± 1.20	0.4 ± 0.2	0.01	4405 - 0
4448.07 ± 1.20	0.5 ± 0.2	0.01	
4478.25 ± 0.90	0.7 ± 0.2	0.02	4478 - 0
4489.19 ± 0.80	6.7 ± 0.6	0.15	4487 - 0
4631.49 ± 0.80	1.4 ± 0.3	0.031	4631 - 0
4655.57 ± 0.70	0.5 ± 0.2	0.01	
4685.64 ± 1.20	0.4 ± 0.2	0.01	4685 - 0
4701.51 ± 0.90	0.5 ± 0.2	0.01	

Table 7. ⁸⁹Kr coincidence information

Gate (keV)	Observed Coincidences (keV)
197	(267), 411, 497, 585, 626, 707, (729), 776, 867, 997, 1533, 1903, 2400
205	(490), (557), (1172)
220	356, 364, (411), 438, 466, 696, 710, (738), 776, 904, 974, 1103, 1116, 1172, (1273), 1472, 1634, 1643, 1777, (1868), 1939, 2377, 2645, 2793, 2878, 3029, 3107, 3140, 3827, 3923, 3977, 4184
264	345, 497, (629), 710, 930
338	437, 626, 974, 1235, 1600
345	220, 264, (557), 585, 762
356	220, 762, 1116, 1421, (1582), (1823), 2021, 2793, 3140
364	220, 738
369	466, 407, 738, 904, 1103, 1324, 1634
402	197, (380), (674), (1067), (1131), 1500, 1777

Table 7. (Continued)

Gate (keV)	Observed Coincidences (keV)
411	197, 220, 490, 585, (626), 696, 904, (1868), 1162
438	338, 466, 629, 835, 1162, 1324, 1939, 2160
466	220, 438, 762, 857, 1107, 1116, 1472, 1693
490	411, 776, (997)
497	197, 264, 402, 466, 826, 904, 974, (1195), 1367, 1500, (1721), 1903, 2100, 2873, 3219, 3732, 3853
557	345, 710, 930, 1839
576	(747), 762, (953), 1116, 1421, (1582), (1634), (1788), (1810), 2021, 2793, 3140, 3257, (3321)
585	197, 345, 369, 411, 696, 738, (953), 835, (944), 1044, 1107, 1172, 1235, 1273, 1412, 1555, 1573, (1683), 2012, (2195), 2280, 2878, 2946, (3781), 3901
626	197, (264), 338, 974, 1044, 1506
629	(944), (953), 1530
696	411, 585, 776, 904, 997, 1172, 1634
707	197, 220, (380), (696), 738, 762, 960, 1472, 1693
710	220, 264, 557, 626, 762
729	(904), (1273), (1472), (1693)
738	364, 369, 585, 835, 1076, 1273, 2046
762	345, 356, 576, 585, 710, 904, 930, 1172
776	197, 220, 490, (626), 696, 904
826	497, 369, 835, 1273
835	438, 585, 738, 857, 1103, 1324
857	466, 835, 1939
867	197, (380), 960, 1131, 1533, 2853
904	220, 267, 369, 411, 497, 576, 585, 696, (729), 738, 762, 776, 1107, 1116, 1324, 1472, 1693
930	264, (557), (626), 762
944	(364), (585)
953	220, 356, 576
960	497, (707), 867, 1593, (1903)

Table 7. (Continued)

Gate (keV)	Observed Coincidences (keV)
974	220, 497, 626, (668), 904, (964)
997	197, (490), 696, (1162)
1044	626, 1235
1076	197, 738, 1103, 1324
1088	(369), (762), (1107), (1116), (1472)
1103	220, 369, 835, 1273
1107	220, 364, 466, 585, 707, 904, (1088), 1172, 1634
1116	356, (466), 576, 707, 904, (1088), 1172
1131	(402), 867
1162	411, 438, 585, 776, 997
1172	369, 738, 1107, 1116, 1472, 1693
1228	(242), 345, 930
1235	338, 585, 1044, 1506
1273	267, 585, 738, 826, 1103, 1324
1324	369, 438, (674), 835, 1076, 1273, (1464), (1634), (1692), 2046
1367	497
1412	(402), 585, (599)
1421	356, (402), 576
1472	220, 466, 707, 904, (1088), 1172, 1634
1500	402, 497, 599
1506	(626), 1235
1530	629, (1335)
1533	197, 867, 960
1555	364, 585, 1186
1573	(364), 438, 585
1582	220, 356, 438, 576
1600	220, (338)
1634	369, 696, 738, 1107, 1116, 1472, 1693

Table 7. (Continued)

Gate (keV)	Observed Coincidences (keV)
1643	220, (295)
1667	497, (762), 1472
1683	364, 585
1693	(304), 466, (671), 707, (738), 904, (1088), 1103, 1172, 1324, 1634
1721	497
1777	220, 402, (599), (783)
1788	(356), (576)
1810	356, 576
1839	411, 490, 557
1868	(411)
1903	197, 497
1939	220, 438
2012	(267), 364, 585
2021	356, 576
2046	738, 1324
2100	497
2160	(242), 438
2195	364, 585
2280	364, 585
2377	220, (267)
2400	197
2645	220
2793	220, 356, 576
2853	867
2873	497
2878	585
3029	220

Table 7. (Continued)

Gate (keV)	Observed Coincidences (keV)
3107	220
3140	220, 356, 576
3219	498
3399	220, 356, (576)
3583	497
3732	497
3781	585
3827	220
3842	497
3901	585
3923	220
3977	220
3995	220
4184	220

indicated. No attempt was made to resolve the 197- and 497-keV doublets in the coincidence gates and the resulting information in Table 7 includes coincidences appropriate to both peaks in each doublet. Figure 16 is the level scheme for ^{89}Rb with the gamma-ray energy, intensity per 100 beta decays of ^{89}Kr , and the coincidence information indicated as for the ^{89}Sr level scheme. Note that the level spacings as drawn are not necessarily proportional to the energy differences between levels.

In the only previous comprehensive study of ^{89}Kr decay, by Kitching and Johns (13), many of the major levels in ^{89}Rb were established and are confirmed by the present experiment. Levels at 220.90, 497.5, 576.96, 585.80, 997.35, 1324.28, 1693.70, 1998.5, 2160.02, 2400.99, 2598.1, 2866.2, and 3532.8 keV are established in this work by much energy sum and coincidence information and corresponding levels were reported by Kitching and Johns. All of the above excited levels except the 1998.5- and 2598.1-keV levels have quite strong ground-state transitions. A brief examination of the level scheme indicates the large amount of information which is available to support the establishment of these levels, and they will not be discussed further here except as they are involved with the establishment of other levels.

The 1533-, 3364-, and 3720-keV levels observed by Kitching and Johns have corresponding levels in the present work. However, additional comments are called for in the discussion of these levels and will be made later. No level is seen in the present work to correspond to the 1770-keV level proposed by Kitching and Johns. Depopulating gamma rays attributed by them to that level are placed elsewhere in the present scheme.

Figure 16. The ^{89}Rb level scheme (continued)

Figure 16. The ^{89}Rb level scheme (continued)

As noted earlier, the 1530.04- and 1533.68-keV gamma rays are well resolved in the singles spectra and can be distinguished relatively easily in the coincidence gates. The 1530.04-keV photopeak is established as the ground-state transition from that level. The 629.75-keV gamma ray is in coincidence with the 1530.04-keV gamma ray and the cascade energy sum corresponds to the 2160.02-keV energy level. Additional coincidence information establishes cascades depopulating the 1530.04-keV level through the 585.80- and 576.96-keV levels to the ground state.

The 1533.68- and 867.08-keV gamma rays are in strong coincidence and the cascade depopulates the 2400.99-keV level. Coincidences are indicated between the 960.42-keV transition, which populates the 2400.99-keV level, and several gamma rays which depopulate the level as well as the 1533.68- and 867.08-keV cascade. A level is established then at 867.08 keV since the relative intensity of the 867.08-keV transition exceeds that of the 1533.68-keV transition by about 15%. If a level is established at 1533.68 keV, no transitions are found to lower levels to aid in depopulation of that level, and gamma-ray population to such a level would exceed depopulation. In addition, the 2853.25-keV gamma ray is seen to be in coincidence with the 867.08-keV gamma ray, but not with the 1533.68-keV gamma ray, indicating that the cascade goes through a level at 867.08 keV.

The level at 930.95 keV is established by depopulating transitions in coincidence with the 220.90- and 585.80-keV transitions and a ground-state transition. The strong 762.87-keV gamma ray is seen to populate the 930.95-keV level from the 1693.70-keV level (the 762.87-keV transition appears in coincidence with the 576.96- and 356.06-keV transitions also

as discussed below).

The level at 1195.2 keV was established initially on the 974.39-keV transition coincidence with the 220.60-keV gamma ray. The coincidence of the 974.39-keV and 904.27-keV transitions indicated that a transition existed between the 1693.70- and 1195.2-keV levels, namely the 498.60-keV transition. The 498.60-keV photopeak was found to be in coincidence with the 974.39-keV transition. The 196.24-keV transition was found to be in coincidence with transitions depopulating the 997.35-keV level with coincidence strength that could not be accounted for by feeding from the 197.46-keV transition above, which populates the 2400.99-keV level. In addition, the 626.20-keV transition depopulating the 1821.4-keV level (which is not fed from the 2400.99-keV level) to the 1195.2-keV level is found to be in coincidence with the 196.24-keV gamma ray. Thus the 196.24-keV transition depopulates the 1195.2-keV level to the 997.35-keV level.

The 1339.9-keV level is established primarily on the strength of the 762.87-keV transition coincidence with the 576.96- and 356.06-keV transitions. As has been seen, the 762.87-keV gamma ray depopulates the 1693.70-keV level to the 930.95-keV level and is placed there by coincidence information. A transition from the 930.95-keV level to the 576.96-keV level would have to have an energy of 354.01 keV, would need to be sufficiently intense to account for the coincidence intensity seen between the 762.87- and 576.96-keV photopeaks, and would be quite well-resolved from the 356.06-keV gamma ray. No 354.01-keV gamma ray is seen. Certain strong transitions to the 585.80-keV level, such as the 345.03- and 738.40-keV transitions, are not seen in coincidence with the 576.96-

or 356.06-keV gamma rays. Thus there can be no feeding from the 930.95-keV level to the 576.96-keV level through the 585.80-keV level. The placement of all or part of the 762.87-keV transition between higher levels which feed the 576.96-keV is not supported by any coincidence information. The establishment of the level at 1339.9-keV is the only remaining way to account for the observed coincidence of the 762.87-keV gamma ray with the 576.96- and 356.06-keV gamma rays. A level at 1339.9 keV is also supported by a possible coincidence between the 753.54- and 585.80-keV transitions, and a ground-state transition. About 30% of the 762.87-keV gamma-ray intensity is assigned to the depopulation of the 1339.9-keV level on the basis of coincidence gate intensities.

The 1488.13-keV level is supported by coincidences between the 490.76-keV transition and those depopulating the 997.35-keV level, and between the 557.30-keV transition and the transitions depopulating the 930.95-keV level. The 1821.4-keV level is established by depopulating transitions which have coincidences with some of the intense transitions depopulating the 1195.2-, 585.80-, and 220.90-keV levels. Transitions which have coincidences with the 497.51-, and 220.90-keV photopeaks, as well as four other depopulating gamma rays, establish the 1864.7-keV level.

The levels at 2140.8, 2218.8, 2269.6, 2365.2, and 2387.9 keV are established primarily on the strength of a single piece of coincidence information with 497.51-, 576.96-, or 585.80-keV gamma rays. Few other gamma rays are involved with these levels. The 2781.7-keV level is based on a number of energy sums and a coincidence between the 2195.76-keV

transition and the 585.80- and 364.88-keV transitions. The 2788.8-keV level is established with three depopulating gamma rays and a possible coincidence between the 1464.24- and 1324.28-keV gamma rays.

The 857.37-keV transition coincidences with gamma rays depopulating the 2160.02-keV level establish the level at 3017.9 keV. Six other gamma rays also depopulate the 3017.9-keV level. A definite coincidence between the 3029.16- and 220.90-keV transitions is the basis for the 3250.1-keV level.

The 3327.6-, 3361.7-, and 3370.9-keV levels are established by many transitions and coincidences with gamma rays depopulating major levels. The closely spaced 3361.7- and 3370.9-keV levels correspond to the 3364-keV level observed by Kitching and Johns. The 3465.0-keV level is based on the coincidence seen between the 2878.69- and 585.80-keV transitions.

The 3717.5-keV level is based on a strong ground-state transition and coincidences between other depopulating gamma rays and the 576.96- and 497.5-keV gamma rays. This level corresponds to the 3720-keV level seen by Kitching and Johns. In addition, a level at 3719.8 keV established in this work is based on the coincidence between the 2853.25- and 867.08-keV transitions noted earlier. The 3834.0-keV level is established on the basis of a single gamma ray, the 3257.02-keV transition, which is seen in coincidence with the 576.96-keV gamma ray.

The level at 3965.5 keV is established by energy sums and the 3965.53-keV ground-state transition which is not seen in the total coincidence profile, indicating that it depopulates a level fed primarily by beta

decay. The level at 3977.5 keV is based on a coincidence between the 3399.88- and 576.96-keV transitions. A strong gamma ray at 3977.54 keV is seen and approximately 25% of the intensity of this gamma ray is seen in coincidence with the 220.90-keV gamma ray and establishes a level at 4198.4 keV. The remaining 75% of the intensity is attributed to the ground-state transition from the 3977.5-keV level.

Coincidences with the 220.90-, 497.51-, or 585.80-keV gamma rays by transitions from levels at 4048.6, 4080.6, 4143.6, 4198.4, 4216.4, 4230.9, 4340.6, 4367.3, 4405.0, and 4487.7 keV help establish these levels. Levels at 4307.2, 4338.4, 4478.4, 4631.1, and 4685.9 keV are established on energy sums alone.

Four levels in this level scheme are dashed in the level scheme drawing, indicating a lesser degree of confidence in their existence. The levels at 2218.8, 3834.0, and 4198.4 keV are based on a single gamma ray while the level at 4685.9 keV is based on very low-intensity transitions.

G. Beta Branching from ^{89}Kr Decay and Log ft's

The percent beta branching from ^{89}Kr decay was determined with the aid of an equilibrium experiment. Comparison of the areas of the 1031.88- and 1248.10-keV gamma rays of ^{89}Rb decay with the areas of the 220.90- and 585.80-keV gamma rays of ^{89}Kr decay provided a normalization factor of 2.823 ± 0.114 between the two decays, which made it possible to directly compare gamma-ray depopulations to get the ground-state feeding to ^{89}Rb . The total gamma-ray depopulation to the ground state in ^{89}Rb was multiplied by this normalization factor, and intensity corresponding

to the 18% ground-state beta branching in the ^{89}Rb decay was added to the ground-state gamma-ray intensities. Then comparing this total decay intensity of ^{89}Rb with the intensity of the ground-state gamma-ray transitions in ^{89}Kr , it was determined that $14 \pm 2\%$ of the total beta decay of ^{89}Kr is to the ground state of ^{89}Rb . This result contrasts sharply with the 0.1% beta branching to the ground state of ^{89}Rb reported by Kitching and Johns (13). A ground-state beta feeding of 14% was used to calculate the beta feeding to all other ^{89}Rb levels in this work. A Q_β of 5.15 ± 0.03 MeV, reported by Kitching and Johns, was obtained by attributing the highest energy beta group observed (with a 4.90 ± 0.03 MeV endpoint energy) to the 220.90-keV level. As is seen in the proposed decay scheme, no beta feeding is attributed to the 220.90-keV level by this experiment. A preliminary result for Q_β for ^{89}Kr decay using beta-gamma coincidence techniques done by Clifford *et al.* (45) gives a value of 4.878 ± 0.049 MeV. The discrepancies noted in Q_β and the percent beta branching to the ^{89}Rb ground state will be discussed further in Chapter V.

The log ft values for the levels of ^{89}Rb were calculated assuming a value of 4.878 MeV for Q_β . A statistical shape for the beta spectrum is assumed and atomic screening is used. Table 8 gives the excited levels in ^{89}Rb , the percent beta feeding to each level, and the associated log ft value.

Table 8. Percent beta branching and log ft's for ^{89}Kr decay

^{89}Rb Levels (keV)	Beta Group Energy (MeV)	Percent Beta Branching	Log ft
0.0	4.88	14	7.2
220.90	4.66	~ 0	---
497.5	4.38	1.23	8.1
576.96	4.30	4.39	7.5
585.80	4.29	2.56	7.7
867.08	4.01	0.19	8.7
930.95	3.95	0.51	8.2
997.35	3.88	1.53	7.7
1195.2	3.68	~ 0	---
1324.28	3.55	4.04	7.1
1339.9	3.54	0.70	7.9
1488.13	3.39	0.02	9.3
1530.04	3.35	3.20	7.1
1693.70	3.18	11.42	6.5
1821.4	3.06	0.25	8.0
1864.7	3.01	0.53	7.7
1998.5	2.88	2.34	7.0
2140.8	2.74	0.003	9.8
2160.02	2.72	3.20	6.7
2218.8	2.66	0.25	7.8
2269.6	2.61	0.089	8.2
2365.2	2.51	0.22	7.7
2387.9	2.49	0.35	7.5
2400.99	2.48	6.35	6.3
2598.1	2.28	16.68	5.7
2781.7	2.10	1.69	6.5
2788.8	2.09	0.31	7.3
2866.2	2.01	4.50	6.0
3017.9	1.86	0.74	6.7

Table 8. (Continued)

⁸⁹ Rb Levels (keV)	Beta Group Energy (MeV)	Percent Beta Branching	Log ft
3250.1	1.63	0.30	6.8
3327.6	1.55	2.25	5.9
3361.7	1.52	1.77	5.9
3370.9	1.51	2.60	5.8
3465.0	1.41	0.35	6.5
3532.8	1.35	1.67	5.8
3717.5	1.16	2.68	5.3
3719.8	1.16	0.37	6.2
3834.0	1.04	0.58	5.7
3898.6	0.98	0.19	6.2
3965.5	0.91	0.22	6.0
3977.5	0.90	0.50	5.6
4048.6	0.83	0.56	5.4
4080.6	0.80	0.77	5.2
4143.6	0.73	0.62	5.2
4198.4	0.68	0.082	6.0
4216.4	0.66	0.20	5.5
4230.9	0.65	0.23	5.4
4307.2	0.57	0.16	5.4
4338.4	0.54	0.18	5.3
4340.6	0.54	0.24	5.1
4367.3	0.51	0.66	4.6
4405.0	0.47	0.19	5.0
4478.4	0.40	0.40	4.5
4487.7	0.39	0.62	4.3
4631.1	0.25	0.67	3.6
4685.9	0.19	0.096	4.1

V. DISCUSSION OF RESULTS

In the present chapter, the level schemes of ^{89}Sr and ^{89}Rb will be discussed in an attempt to shed some light on nuclear structure near mass 89. It must be pointed out at the outset that, in this study of gamma-ray de-excitation of daughter nuclei following the beta decays of ^{89}Kr and ^{89}Rb , no direct measurement of any nuclear parameter was made. Only the indirect evidence of energy levels established by consideration of gamma-ray transitions is available from this experiment. Any knowledge about nuclear structure gained from this experiment will be deduced from consideration of the properties of neighboring nuclei, from theoretical results for this mass region, and by interpretation of the systematics and model predictions for this region. No conclusions drawn in this chapter should be regarded as indisputable fact, but simply as conclusions which seem consistent with the experimental results. Nevertheless, gamma-ray decay studies in the past have proven useful to gain insight into nuclear structure, and it is in this spirit that the discussion below is undertaken.

A. The Closed Shell Region Near Mass 89

The title of this section, somewhat tongue in cheek, typifies discussion of the nuclear region near masses 88 and 90. The shell model points out major shells for neutrons and protons at the magic number 50 (46,47). The proton $2p_{3/2}$, $1f_{5/2}$, and $2p_{1/2}$ subshells below this magic number are quite close in energy and somewhat split from the proton $1g_{7/2}$ subshell. This fact, coupled with the closed $N = 50$ shell,

produces the nearly double magic ^{88}Sr and ^{90}Zr nuclei.

On the basis of shell model theory, one would expect a ground state proton configuration of $\pi(2p_{3/2})^4 (1f_{5/2})^6$ (or $(2p_{1/2})^{-2}$ as it is often written) and a neutron configuration of $\nu(1g_{9/2})^{10}$ for ^{88}Sr . Similarly, the ground state configuration for ^{90}Zr would be $\pi(2p_{3/2})^4 (1f_{5/2})^6 (2p_{1/2})^2 \nu(1g_{9/2})^{10}$. The $1g_{9/2}$ subshell is the last neutron subshell below the magic number $N = 50$. Actually, configuration mixing is found to be present in the ground states of both of these nuclei. A theoretical study by Hughes (48), based on reaction and spectroscopy data, indicates that 70% of the ground state of ^{88}Sr is accounted for by the $\pi(2p_{3/2})^4 (1f_{5/2})^6$ configuration, with the remainder being accounted for by a mixture of $\pi(2p_{3/2})^{-2}$, $\pi(1f_{5/2})^{-2}$, and $\pi(1f_{7/2})^{-2}$ configurations. This calculated 70% closed-shell configuration for the ground state is consistent with the estimate of Shreve (49) from $^{89}\text{Y}(d, ^3\text{He})$ and $^{88}\text{Sr}(d, ^3\text{He})$ reactions that 60 to 80% of the ground state of ^{88}Sr is comprised of the $\pi(2p_{3/2})^4 (1f_{5/2})^6$ configuration. Shastry (50), in his calculation on ^{88}Sr , concludes that configuration mixing is important in the ground state and excited states, but that the mixing should include one-particle-one-hole states rather than the two-particle-two-hole states considered by Hughes (48). In a recent experimental work, Ragaini and Meyer (51) suggest configuration mixing also for the proton states for the first two $2+$ levels in ^{88}Sr . An experiment by Hardy et al. (52) on levels in ^{91}Y supports the ground state configuration mixing picture for ^{88}Sr .

Calculations by Talmi and Unna (53) and Auerbach and Talmi (54), based on experimental data in the ^{90}Zr region, indicate that 60% to 75%

of the ground state of ^{90}Zr is composed of the core proton configuration $\pi(2p_{3/2})^4(1f_{5/2})^6(2p_{1/2})^2$, with the rest being accounting for by $2p_{1/2}$ and $1g_{9/2}$ proton mixing. Excited levels also exhibit these mixed configuration characteristics according to their calculations.

It is important to point out a disturbing ambiguity in these theoretical calculations. Those calculations which showed configuration mixing to be important in ^{90}Zr assumed that ^{88}Sr was a closed shell nucleus, that is, only $2p_{1/2}$ and $1g_{9/2}$ proton subshells were considered in the configuration mixing. The ^{88}Sr configuration mixing calculations assume that two-proton-two-hole operators are acting on the ^{90}Zr core. In addition to the studies cited above, calculations by Bhatt and Ball (55) on Nb, Mo, and Tc isotopes which assumed a ^{90}Zr core, and calculations by Vervier (56), who used a ^{88}Sr core for isotopes of Y, Zr, and Nb and a ^{90}Zr core for isotopes of Nb, Mo, and Tc, have been performed yielding results consistent with the core nucleus choices. In the words of Hardy et al. (52), "All authors conclude from comparison with rather meagre experimental evidence that the assumed shell closures were justified." This, of course, is not a criticism of these efforts, but reflects the difficulty of dealing with this region which appears at first glance to be amenable to easy shell model treatment, but is found not to be.

From an early discussion of core excitations in nondeformed, odd A nuclei by de-Shalit (57), and through the treatments of several nuclei including ^{59}Ni (58) and ^{207}Pb (59) by particle-core coupling, an increasingly important role has been played by particle-core coupling in

explaining the nuclear structure of odd A nuclei near closed shells. The particle-core coupled levels have a highly collective nature that becomes apparent in reaction studies. Hughes (48) and Auerbach (60) considered the coupling of the $2d_{5/2}$ neutron and the ^{88}Sr core vibration states in their calculations of the ^{89}Sr nuclear structure. They found that this particle-core coupling was important in the interpretation of several excited levels in ^{89}Sr .

The above discussion, then, indicates the kind of interpretations of levels and transitions that are to be expected in the analysis of the ^{89}Sr level scheme. The ground state and excited levels in this nucleus are expected to exhibit single-particle character with possible configuration mixing, as well as some levels being identified as coupled single-particle states and core vibrations. The gamma-ray transitions, both present and absent, may lead to distinction of single-particle levels from particle-core coupled levels by consideration of reduced transition probabilities. Evidence from reaction studies is important in narrowing the possibilities in interpretation of the ^{89}Sr level scheme.

B. Discussion of the ^{89}Sr Level Scheme

In terms of the shell model states, the bulk of the ground state configuration for ^{89}Sr is $\pi(2p_{3/2})^4(1f_{5/2})^6\nu(1g_{9/2})^{10}(2d_{5/2})^1$. This configuration would imply a spin and parity assignment of $5/2^+$ for the ground state of ^{89}Sr . This J^π assignment is amply supported in several ways. The spin of the ^{89}Y ground state is measured to be $1/2$ by atomic spectroscopy (61). With this spin arising from a $\pi(2p_{3/2})^4(1f_{5/2})^6(2p_{1/2})^1\nu(1g_{9/2})^{10}$ configuration, the parity would be

negative. The $9/2^+$ isomeric level in ^{89}Y at 909 keV is known to have an M4 transition to the ground state (62,63). A second forbidden beta transition between the ^{89}Sr ground state and the $9/2^+$ state in ^{89}Y has been observed (43,44), which is consistent with a $5/2^+$ assignment to the ^{89}Sr ground state. Further, the $^{88}\text{Sr}(d,p)^{89}\text{Sr}$ reaction studies (19-22) indicate that the ground state of ^{89}Sr is populated by an $l_n = 2$ stripping reaction, consistent with a $5/2$ spin assignment. The $^{88}\text{Sr}(p,p)$ and $^{88}\text{Sr}(p,p')$ isobaric analogue reaction studies (23,24) are also consistent with a $5/2^+$ assignment to the ^{89}Sr ground state.

In order to discuss adequately the excited levels of ^{89}Sr , the nature of the ground state of ^{89}Rb must be known also. A reasonable shell model configuration for the ^{89}Rb ground state is $\pi(2p_{3/2})^3(1f_{5/2})^6 \nu(1g_{9/2})^{10}(2d_{5/2})^2$. A survey of the spin and parity assignments for Rb isotope ground states (64) gives the following results: ^{79}Rb is probably $3/2^-$, ^{81}Rb is $3/2^-$, ^{83}Rb and ^{85}Rb are $5/2^-$, and ^{87}Rb is $3/2^-$. A $3/2^-$ assignment to the ground state of ^{89}Rb , which would result from the above shell model configuration, is thus consistent with the trends for the ground state in rubidium isotopes.

The 18% ground-state beta branch from ^{89}Rb to the ground state of ^{89}Sr yields a log ft value of 7.6, consistent with the first forbidden transition ($\Delta J = 0, \pm 1$, yes) that would be expected. One $2d_{5/2}$ neutron beta decays into a $2p_{3/2}$ proton with the second neutron remaining in the $2d_{5/2}$ subshell. Thus, in the simplest shell model picture, the ^{89}Rb and ^{89}Sr ground state configurations are:

$$^{89}\text{Rb}; \quad \pi(2p_{3/2})^3(1f_{5/2})^6 \nu(1g_{9/2})^{10}(2d_{5/2})^2$$

and $^{89}\text{Sr}; \quad \pi(2p_{3/2})^4(1f_{5/2})^6 \nu(1g_{9/2})^{10}(2d_{5/2})^1.$

It can be seen that, in general, the decay of ^{89}Rb to the ^{89}Sr ground state and lower excited states of ^{89}Sr will involve the decay of a $2d_{5/2}$ neutron into a $2p_{3/2}$ or possibly $1f_{5/2}$ proton, and would then be a first forbidden transition.

It is important here to point out that the beta decay interaction Hamiltonian, which was first proposed by Fermi (65) and is used to describe beta decay, is a single-particle interaction. From a field-theoretic point of view, a neutron and a neutrino are annihilated at one point and a proton and an electron are created at the same point. No particles other than the four taking part in the interaction at that one point are involved in the beta decay. This consideration is important, for it rules out processes in which one neutron is annihilated and one proton created and simultaneously a second neutron or proton is caused to change energy state. Thus, for example, for pure single-particle states, beta decay to ^{89}Sr which would leave the neutron outside the $N = 50$ closed shell in any subshell other than the $2d_{5/2}$ subshell could not occur.

Knowing, then, what the nature of the ground states of ^{89}Rb and ^{89}Sr is, the type of interaction that is taking place in beta decay, and the configurations to be expected of the excited levels of ^{89}Sr , the level scheme of ^{89}Sr can be analyzed. Using the selection rules for beta decay

and electromagnetic transitions, and the aid of knowledge gained through reactions and theoretical studies, spins and parities will be assigned to excited levels where possible, and state configurations will be proposed.

The first excited level of ^{89}Sr is at 1031.38 keV. Previous reaction and spectroscopic studies give this level a $1/2^+$ assignment (13,22), indicate that it is largely single-particle in nature, and suggest that its shell model configuration is $\pi(2p_{3/2})^4(1f_{5/2})^6\nu(3s_{1/2})^1$. In the present work no beta decay is seen to this level. For strict single-particle shell model states, this result would be expected in light of the above discussion of the beta decay interaction. It would not be possible for one of the $2d_{5/2}$ neutrons to decay into a $2p_{3/2}$ proton, while the second $2d_{5/2}$ neutron is simultaneously promoted to the $3s_{1/2}$ subshell. In considering configuration mixing, the absence of beta decay to this level is consistent with the conclusion that either the ^{89}Rb ground state has no $\nu(3s_{1/2})$ component, or the 1031.88-keV level has no $\nu(2d_{5/2})$ mixing, or both.

The 2007.54-keV level in ^{89}Sr has a beta branch with a log ft value of 8.1, indicating a first-forbidden beta transition. Reaction studies, particularly those of Cohen (19), indicate that this level had a J^π of $3/2^+$. This assignment could arise from a shell model configuration of $\pi(2p_{3/2})^4(1f_{5/2})^6\nu(2d_{3/2})^1$. Angular distributions of protons from (d,p) stripping reactions indicate that the 2007.54-keV level is largely single-particle in nature. A calculation of the ratios of E2 reduced transition probabilities between this level and the $3s_{1/2}$ and $2d_{5/2}$

levels from the observed transition intensities gives

$$\frac{B(E2, 3/2 \rightarrow 1/2)}{B(E2, 3/2 \rightarrow 5/2)} = 0.90 \pm 0.26$$

in good agreement with a Weisskopf estimate of 1. Thus the observed transition intensities are consistent with the single-particle states. M1 transition mixing is ruled out by angular momentum considerations for transitions between the $2d_{5/2}$ and $3s_{1/2}$ single-particle states but not necessarily for transitions between the $2d_{3/2}$ and $2d_{5/2}$ levels. The fact that beta decay branching is observed to the 2007.54-keV level indicates the presence of configuration mixing in either this level, the ^{89}Rb ground state, or both. The 2007.54-keV level could be predominantly $\nu(2d_{3/2})^1$ with $\nu(2d_{5/2})^1$ admixture while the ^{89}Rb ground state could be predominantly $\nu(2d_{5/2})^2$ with $\nu(2d_{5/2})^1$, $(2d_{3/2})^1$ and $\nu(2d_{3/2})^2$ mixing.

The level at 1473.22 keV is the lowest particle-core coupled level appearing in this study. The particle-core coupled nature is supported by the nonstripping shape of the outgoing proton distribution in (d,p) reactions (22). The experimental log ft value of the beta branch to this level of 8.7, using a statistical beta spectrum shape, is somewhat higher than the log ft values of the first forbidden transitions to the ^{89}Sr ground state and the 2007.54-keV level. If a unique shape is assumed for the beta decay spectrum to this level, a log ft value of 9.1 is obtained, indicating a unique first forbidden transition ($\Delta J = \pm 2$, yes). Hughes' calculations on ^{89}Sr puts a $7/2^+$ level at about 1500 keV (48). A radiative transition from the 1473.22-keV level to the $3s_{1/2}$

level would be M3 or E4 and improbable. Indeed, this transition does not appear in the present work. Thus, the 1473.22-keV level is reasonably considered to have a J^π of $7/2^+$ and can be regarded as the result of coupling of a $\pi(2p_{3/2})^4(1f_{5/2})^6 \nu(2d_{5/2})^1$ particle configuration with the first 2^+ vibration of the "core" nucleus, ^{88}Sr , at 1836.09 keV.

A log ft value of 8.4 for the beta branch to the level at 1940.23 keV is probably a non-unique first forbidden transition since a unique first forbidden transition would require a $7/2^+$ assignment to this level. Stripping reaction studies (22) indicate an angular momentum transfer of $l_n = 2$ from the 0^+ ground state of ^{88}Sr for a possible $3/2^+$ or $5/2^+$ assignment. The transition present to the $7/2^+$ level at 1473.22 keV constitutes evidence against a $1/2^+$ assignment to the 1940.23-keV level. Thus, this level appears to have spin-parity of $3/2^+$ or $5/2^+$. The nature of this level is somewhat in question. Proton angular distributions seen in stripping reactions seem to indicate a single-particle nature for this level (22). However, the spectroscopic factor is quite small, indicating other origins. This level could be visualized as the second particle-core coupled state formed from the $\pi(2p_{3/2})^4(1f_{5/2})^6 \nu(2d_{5/2})^1$ configuration and the first 2^+ collective level of ^{88}Sr .

The 2058.0-keV level corresponds in energy with nonstripping levels seen at 2057 and 2071 keV in stripping reactions (22). A log ft value of 8.0 for the beta transition to this level indicates a first forbidden transition and a resulting J^π assignment of $1/2^+$, $3/2^+$, or $5/2^+$. None of these can probably be ruled out on the basis of transitions to other levels because of the overall low intensities involved. Hughes (48)

Indicates the presence of a $9/2^+$ level at this energy and speculates that the second level seen in reaction studies may be $11/2^-$. Recently a $11/2^-$ level at 2070 keV has been observed in a $^{88}\text{Sr}(d,p)$ reaction study (66). It seems improbable that the 2058.0-keV level is either a $9/2^+$ or $11/2^-$ since these spin and parity assignments would be likely to render beta decay to this level unobservable. This level, with the J^π assignment indicated by the log ft value, could again be a coupling of the $\pi(2p_{3/2})^4(1f_{5/2})^6 \nu(2d_{5/2})^1$ configuration and the 2^+ first excited level in ^{88}Sr .

The 2280.0-keV level has a beta branch with a log ft value of 6.0, probably too low for a first forbidden transition in this mass region. Thus, the beta transition to this level is probably allowed ($\Delta J = 0, \pm 1$, no) and the resultant possible J^π assignments are $1/2^-$, $3/2^-$, and $5/2^-$. The $5/2^-$ assignment would require an M2 or E3 transition to the first excited state which would be of low intensity compared to the competing de-excitations. The presence of the very intense 1248.10-keV transition from this level to the $1/2^+$ 1031.88-keV state rules out the $5/2^-$ possibility. The $1/2^-$ assignment would require an M2 or E3 transition to the ground state with intensity inconsistent with that seen for the 2280.06-keV transition in this work. A $3/2^-$ assignment to this level would be consistent with the transitions observed, assuming E1 multipolarities. Comparison of the calculated E1 reduced transition probability ratios with observed intensity ratios support this assignment. Reaction studies indicate that this state is highly collective in nature (22). A $3/2^-$ state could be interpreted as $\pi(2p_{3/2})^4(1f_{5/2})^5 \nu(2d_{5/2})^1$ shell model

configuration coupled to the 3^- core excitation at 2734.14 keV in ^{88}Sr .

The level at 2451.7 keV has a beta branch with a log ft value of 8.2 and can be considered to be a first forbidden transition with a J^π assignment of $1/2^+$, $3/2^+$, or $5/2^+$. Reaction studies eliminate the $1/2^+$ assignment and tend to support the $3/2^+$ assignment (22). Although the proton angular distribution indicates that the level has some single-particle nature, the spectroscopic factor obtained indicates some collective contributions. The particle-core coupling of the $2d_{5/2}$ neutron and the $2^+ \text{ } ^{88}\text{Sr}$ core vibration would again offer a reasonable structure for this level.

Reaction studies indicate that a level at 2670 keV is largely single-particle in nature and suggest that it is the $1g_{7/2}$ level (22,24). The only two levels in this experiment that correspond closely in energy to this value are the levels at 2707.20 and 2570.14 keV. The log ft values for beta branches to these two levels are 6.7 and 6.8, respectively, more indicative of first forbidden transitions than of the unique first forbidden transitions that would be required for a $3/2^-$ to $7/2^+$ beta transition. A possible explanation for this situation would be that ^{89}Rb has some $\nu(2d_{5/2})^1(1g_{7/2})^1$ and or $\nu(2d_{3/2})^1(1g_{7/2})^1$ configuration mixing in the ground state. Then the beta transition could be non-unique first forbidden to a $1g_{7/2}$ proton state from the mixed configuration. A $7/2^+$ assignment to the 2707.20-keV level is consistent with the fact that no transition is seen to the $3s_{1/2}$ level.

The 2570.14-keV level could then have J^π of $1/2^+$, $3/2^+$, or $5/2^+$ on the basis of the log ft value for the populating beta transition. No

gamma-ray transition is seen from the 2570.14-keV level to the $7/2^+$ level at 1473.22 keV, thus making a $5/2^+$ assignment to the 2570.14-keV level unlikely. This level could be viewed as a particle-core coupled level with the $\nu(3s_{1/2})^1$ configuration of the 1031.38-keV level coupled to the 2^+ collective state of ^{88}Sr ; however, this description does not allow a $1/2^+$ assignment.

The level at 3227.9 keV has a beta branch log ft value of 5.0, indicating that it is populated by an allowed beta transition ($\Delta J = 0, \pm 1$, no), and has a possible J^π assignment of $1/2^-$, $3/2^-$, or $5/2^-$. The strong 2196.00-keV transition to the $3s_{1/2}$ level rules out the $5/2^-$ assignment. The other reasonably strong transitions are to $3/2^-$, $3/2^-$, and $3/2^+(5/2^+)$ levels, but a very weak transition is observed to the $5/2^+$ ground state. These transitions, taken together, indicate that the 3227.9-keV level is $1/2^-$. The $1/2^-$ assignment is in agreement with a previous spectroscopic assignment (13), but is not supported by reaction studies. The $1/2^-$ assignment is also consistent with a $\pi(2p_{3/2})^4(1f_{5/2})^6 \nu(2d_{5/2})^1$ single-particle configuration coupled to the first 3^- collective state in ^{88}Sr .

The 3303.5-keV level has a beta branch with a log ft value of 8.1, indicating that this beta transition is first forbidden. Transitions to the $1g_{7/2}$ level and the ground state, in conjunction with the (non-unique) beta transition possibilities, favor a $5/2^+(3/2^+)$ assignment for this level. Reaction studies tend to support the $5/2^+$ assignment (22). This level could be viewed as the second member of the coupling between the $3s_{1/2}$ single-particle state and the 2^+ core vibration in ^{88}Sr , as

supported by the low observed spectroscopic factor.

The log ft value for the beta branch to the 3508.8-keV level is 5.9, indicating an allowed transition. A $5/2^-$ assignment is consistent with all the gamma transitions seen and the fact that no transition is seen to the $3s_{1/2}$ first excited level. This level could be another coupling of the $2d_{5/2}$ neutron level and the 3^- collective level in ^{88}Sr .

The levels at 3651.7 and 3845.7 keV have beta transition log ft values of 6.9 and 6.8 respectively, indicating positive parity. The level at 3845.7 keV has transitions to $7/2^+$, $7/2^+$, and $5/2^+$ levels, consistent with a J^π of $3/2^+$ or $5/2^+$. None of the possible spin and parity assignments of $1/2^+$, $3/2^+$, and $5/2^+$ for the 3651.7-keV level can be eliminated on the basis of the transitions seen. Little can be said about the levels at 3988.1, 4049.2, and 4093.7 keV. The log ft values for beta transitions to these levels are 6.4, 6.1, and 5.8, respectively. The 4093.7-keV level could possibly have negative parity.

Thus, in the ^{89}Sr level scheme, the $2d_{5/2}$, $3s_{1/2}$, $2d_{3/2}$, and $1g_{7/2}$ shell model single-particle states are seen. These are the positive-parity neutron states available for a single neutron between the $N = 50$ and $N = 82$ shells. The $1/2^+$, $3/2^+$, $5/2^+$, and $7/2^+$ couplings of the $2d_{5/2}$ neutron state to the 2^+ collective state in ^{88}Sr are seen, as well as the $3/2^+$ and $5/2^+$ couplings of the $3s_{1/2}$ and the 2^+ state. The $9/2^+$ level of the $2d_{5/2}$ and 2^+ particle-core coupling is not seen; however, on the basis of spin considerations, this would not be unexpected. The weighted average energy of the $2d_{5/2}$ and 2^+ coupled states in ^{89}Sr (assuming that the $9/2^+$ level is at about 2080 keV as calculated by Hughes (48)) is

1935 keV, quite close to the energy of the first 2^+ level in ^{88}Sr which is 1836.09 keV. The difference in energy between the weighted average positions of the $2d_{5/2}$ and 2^+ coupled states (again assuming that the $9/2^+$ level is at about 2080 keV) and the $3s_{1/2}$ and 2^+ coupled states is 1103 keV, in good agreement with the 1031-keV energy difference between the $2s_{5/2}$ and $3s_{1/2}$ single-particle levels. In addition to the coupled states mentioned, the $1/2^-$, $3/2^-$, and $5/2^-$ levels resulting from the coupling of the $2d_{5/2}$ neutron and the 3^- collective state in ^{88}Sr are seen. A recent $^{88}\text{Sr}(\alpha, n\gamma)$ study of ^{91}Zr (67) indicates that many of the low-lying levels in that nucleus can be accounted for by single-particle and particle-core coupled state configurations. It seems that ^{89}Sr is another nucleus in which this picture is useful in understanding its nuclear structure.

Figure 17 summarizes the level assignments in this work for ^{88}Sr and compares them with the low-lying ^{88}Sr levels (68-71) to emphasize the collective nature of some of the ^{89}Sr levels. Level energies, spin and parity assignments, and possible level configurations which appear consistent with the experimental results and assigned spins and parities are shown. The splittings of the collective states in ^{88}Sr , due to particle-core coupling, are shown connected to the respective states in ^{89}Sr .

Figure 18 compares the levels of ^{89}Sr with the low-lying levels of neighboring nuclei that have 51 neutrons and might be expected to have a structure similar to that of ^{89}Sr . Comparisons are made with ^{87}Kr (72,73), ^{91}Zr (67), ^{93}Mo (74-76), and ^{95}Ru (77), and the trends of the main levels

Figure 17. The ^{89}Sr level scheme with spin and parity assignments shown, and with possible particle-core coupling configurations and associated ^{88}Sr levels indicated

Figure 18. A comparison of ^{89}Sr levels with those of neighboring isotones

are followed. As can be seen, the main point of comparison between these five nuclei is in the ground state and the first excited state. The ground state in all five nuclei is $5/2^+$ which would be expected because of the odd $2d_{5/2}$ neutron. The first excited level is $1/2^+$ in these nuclei and decreases in excitation energy from 1205 keV in ^{91}Zr , to 532 and 779 keV in ^{87}Kr and ^{95}Ru , respectively. Above the $1/2^+$ level, no direct comparisons between these isotones can be made, except possibly between ^{89}Sr and ^{91}Zr , where many of the particle-core coupled states have been seen. In all nuclei, a proliferation of $1/2^+$ to $9/2^+$ levels are seen, which would be consistent with the particle-core coupling model. As protons are added to the ^{89}Sr nucleus, complex couplings between the nucleons appear as evidenced by the observation of a low-lying ($13/2$, $15/2$) state in ^{91}Zr , possibly due to the $2d_{5/2}$ neutron coupling to the 4^- or 5^- proton coupled states arising from the $\pi(3p_{1/2})^1(1g_{9/2})^1$ excited configuration; and the isomeric $21/2$ level in ^{93}Mo , which could be the result of the $2d_{5/2}$ neutron coupling to the seniority two 8^+ proton state.

C. Nuclear Models and ^{89}Rb

Just taking one proton from ^{89}Sr and replacing it with one neutron to make ^{89}Rb may put the nucleus in a whole new class, theoretically speaking. In ^{89}Sr a particle-core coupling model, in which particle states combine with the vibrational states of an even-even core, appears to give a qualitative agreement with what is seen experimentally. While some of the lowest levels of ^{89}Rb can probably be explained on the basis of shell model states as they are in ^{89}Sr , appeal to a more complicated model might

be necessary to explain the proliferation of low-lying excited levels in ^{89}Rb .

Among the features that would need to be reproduced by a valid model for the odd A nuclei with proton numbers from 30 to 38, including ^{89}Rb , are low-lying positive-parity states. An effort is currently being made to explain the excited levels of ^{89}Rb using the Coriolis coupling model (78). Other models will also predict low-lying positive-parity levels including the pairing-plus-quadrupole model which can predict low-lying $9/2^+$ levels (79), and the anharmonic vibrator model which couples the odd particle to a deformed vibrator potential and can predict low-lying $9/2^+$, $5/2^+$ doublets (80). However, these last two models can not predict the large number of low-lying positive-parity levels that result from use of the Coriolis coupling model which can introduce band mixing (81). The Coriolis coupling model has been applied to many nuclei, including isotopes of Rb, by Scholz and Malik (82-85), and to several odd-odd nuclei (86,87). The recent observation of low-lying $1/2^+$ states in four isotopes of As is a strong argument for deformation with strong Coriolis coupling in these proton shells (88). However, for the particular case of ^{89}Rb , the nearness to the closed neutron shell makes uncertain the applicability of a model requiring a deformed core such as the Coriolis coupling model or the anharmonic vibrator model.

D. Discussion of the ^{89}Rb Level Scheme

As discussed in Section B of this chapter, ^{89}Rb probably has a ground-state spin and parity of $3/2^-$ with a shell model configuration of $\pi(2p_{3/2})^3(1f_{5/2})^6\nu(2d_{5/2})^2$. It is necessary to know the J^π assignment

of the ^{89}Kr ground state to be able to use the beta branching information to advantage. The ground-state beta branch to ^{89}Rb is one of the areas of strong disagreement between this work and that of Kitching and Johns (13). The ground-state beta branch of 14% found in this work is much more compatible with a first forbidden beta decay (this would occur from the $5/2^+$ ^{89}Kr ground state, which would be expected on the basis of the shell model, and the $3/2^-$ ^{89}Rb ground state) than is the 0.1% beta branch found by Kitching and Johns. Related to this problem is the one of Q_β for ^{89}Kr decay. Because the previous work (13) attributes no beta branching to the ground state of ^{89}Rb , the highest-energy beta group seen (with an endpoint energy of 4.90 ± 0.03 MeV) is assigned to the first excited level. In this work, no beta feeding is attributed to the first excited level. Indeed, the preliminary Q_β value for ^{89}Kr decay by Clifford (45) of 4.878 ± 0.049 MeV, determined from both beta-gamma coincidences and beta singles measurements, is in good agreement with the highest energy beta group seen by Kitching and Johns (13). Using the ground-state branching found in this work and a Q_β of 4.878 MeV, the calculated log ft for the ground-state beta transition is 7.1, which is in good agreement with that expected for a first forbidden beta transition. The ground state of ^{89}Kr appears, then, to be $\pi(2p_{3/2})^2(1f_{5/2})^6\nu(2d_{5/2})^3$ in terms of shell model states.

No reaction work has been reported on the levels in ^{89}Rb ; thus, in discussing the excited levels of this nucleus, the only available information is the log ft value for the beta branch to each level and the gamma-ray transitions seen between levels. Speculation on the basis of shell

model configurations may be helpful in establishing the nature of low-lying levels.

On the basis of shell model states, it might be expected that the two lowest excited levels in ^{89}Rb would have $5/2^-$ and $1/2^-$ assignments. These assignments can be supported by the following arguments. Using the argument that the beta decay interaction is a single-particle interaction, no beta decay would be seen to the first excited level if it has a $\pi(2p_{3/2})^4(1f_{5/2})^5$ configuration. A $2d_{5/2}$ neutron would have to decay to a $2p_{3/2}$ proton, simultaneously promoting a $1f_{5/2}$ proton to the $2p_{3/2}$ level. This argument is consistent with the fact that no beta decay is observed to the 220.90-keV level. If the 497.5-keV level has $J^\pi = 1/2^-$, a reasonable configuration would be $\pi(2p_{3/2})^2(1f_{5/2})^5(2p_{1/2})^1$. The log ft value of 8.1 could be consistent with the unique first forbidden beta transition required to this level. No transition (which would be E2 and would be easily observable on the basis of single-particle estimates) is seen between the 497.5- and 220.90-keV levels. This might be explained by noting that a gamma transition from the $\pi(2p_{3/2})^2(1f_{5/2})^6(2p_{1/2})^1$ configuration to the $\pi(2p_{3/2})^4(1f_{5/2})^5$ configuration would require the simultaneous change of subshell states by two protons.

In discussing the higher excited levels, information, even on which to base speculation, is lacking. From systematics it is known that a large number of negative parity levels with some low-lying positive levels should be present. Assignment of spins and parities to the higher excited levels is based solely on (sometimes liberal) interpretation of the log ft values and order of magnitude arguments about the multipolarities of transitions.

For example, an $M3, E4$ transition from a $7/2^-$ to a $1/2^-$ level would not be seen if the $7/2^-$ level can depopulate to higher spin levels. These arguments to assign spins and parities to the remaining levels, assuming the assignments to the first three levels, are often circular or pyramid and should not be regarded to be without question. Because of the large number of excited levels in ^{89}Rb , discussion of only eight levels will be presented to give the flavor of the arguments.

930.95- and 997.37-keV levels: The beta branches to these levels have $\log ft$ values of 8.2 and 7.7, respectively, and the beta decays to them are probably first forbidden. Since no transition from either level is seen to the $1/2^-$ second excited level at 497.5 keV, they are given $7/2^-$ assignments. If the beta decay to the 930.95-keV level is considered to be unique first forbidden, that level would have to have a J^π of $1/2^-$ or $9/2^-$, neither of which would be consistent with the transitions seen.

1195.2-keV level: No beta feeding to this level indicates that beta decay to this level is highly forbidden, and gamma transitions to the 997.35-keV $7/2^-$, 930.95-keV $7/2^-$, and 220.90-keV $5/2^-$ levels and a retarded transition to the $3/2^-$ ground state indicate high spin. A $9/2^+$ assignment to this level is proposed and could be due to the $1g_{9/2}$ single-particle level, to which beta decay would be second forbidden.

2598.1-keV level: The $\log ft$ value of 5.7 for the beta branch to this level indicates an allowed beta transition. Strong transitions to the 497.5-keV $1/2^-$ and 220.90-keV $5/2^-$ levels indicate a $3/2^+$ assignment, reinforced by the absence of transitions to the 930.95-keV $7/2^-$,

997.35-keV $7/2^-$, and 1195.2-keV $9/2^+$ levels.

1693.70-keV level: The log ft value of 6.5 probably indicates an allowed beta transition. A strong transition from the 2598.1-keV $3/2^+$ level and strong transitions to the 1195.2-keV $9/2^+$, 997.35-keV $7/2^-$, 930.95-keV $7/2^-$, and 220.90-keV $5/2^-$ levels and the $3/2^-$ ground state suggest a $5/2^+$ assignment.

585.80-keV level: A first forbidden beta decay with a log ft value of 7.6 to this level and strong transitions with the 2598.1-keV $3/2^+$, 1693.70-keV $5/2^+$, 997.35-keV $7/2^-$, 930.95-keV $7/2^-$, and 220.90-keV $5/2^-$ levels and the $3/2^-$ ground state favor a $5/2^-(3/2^-)$ assignment.

2866.14-keV level: The beta branch log ft value of 6.0 indicates an allowed beta transition and, combined with gamma transitions to the $3/2^-$ ground state and the 220.90-keV $5/2^-$, 997.35-keV $7/2^-$, 1693.70-keV $5/2^+$, and 2598.1-keV $3/2^+$ levels, suggests that this level is $5/2^+$.

576.96-keV level: The absence of transitions seen from the 2866.2-keV $5/2^+$, 1195.2-keV $9/2^+$, 997.35-keV $7/2^-$, and 930.95-keV $7/2^-$ levels indicates low spin for this level. Transitions to the 220.90-keV $5/2^-$ level and the $3/2^-$ ground state would indicate a $1/2$ assignment with the negative parity following from the beta branch log ft of 7.4. Note that many of the levels that have strong transitions to either the 585.80- or 576.96-keV levels have comparatively retarded transitions to the other level.

The number of levels to be discussed in this scheme is very large and so the J^π assignments of the remaining levels will not be discussed, but are summarized in Table 9. The spin and parity assignment arguments

Table 9. Tentative spin and parity assignments for ^{89}Rb levels

^{89}Rb Levels (keV)	J^π
0.0	$3/2^-$
220.90	$5/2^-$
497.5	$1/2^-$
576.96	$1/2^-$
585.80	$5/2^- (3/2)^-$
867.08	$1/2^-$
930.95	$7/2^-$
997.35	$7/2^-$
1195.2	$9/2^+$
1324.28	$3/2^- (5/2)^-$
1339.9	$3/2^-, 5/2^-$
1488.13	$9/2^-$
1530.04	$3/2^-$
1693.70	$5/2^+$
1821.4	$7/2^-$
1864.7	$3/2^-, 5/2^-$
1998.5	$3/2^- (5/2)^-$
2140.8	
2160.02	$7/2^-$
2218.8	-
2269.6	-

Table 9. (Continued)

⁸⁹ Rb Levels (keV)	J ^π
2365.2	-
2387.9	-
2400.99	3/2 ⁻ (5/2) ⁻
2598.1	3/2 ⁺
2781.7	3/2 ⁻ , 5/2 ⁻
2788.8	-
2866.2	5/2 ⁺
3017.9	5/2 ⁻
3250.1	-
3327.6	5/2 ⁺ , 7/2 ⁺
3361.7	3/2 ⁺ , 5/2 ⁺
3370.9	3/2 ⁺
3465.0	-
3532.8	+
3717.5	+
3719.8	-
3834.0	+
3898.6	-
3965.5	-
3977.5	+
4048.6	+
4080.6	+

Table 9. (Continued)

^{89}Rb Levels (keV)	J^π
4143.6	+
4198.4	+
4216.4	+
4230.9	+
4307.2	+
4338.4	+
4340.6	+
4367.3	+
4405.0	+
4478.4	+
4487.7	+
4631.1	+
4685.9	+

given for the above levels indicate the general type of arguments used in all other assignments.

In general, it can be seen that a large number of low-lying negative parity levels are populated and four positive parity levels are indicated below 3 MeV. The ground state and the first two excited levels at 220.90 and 497.5 keV, as well as the level at 1195.2 keV, are possible single-particle levels and could be the $\pi(2p_{3/2})^{-1}$, $\pi(1f_{5/2})^{-1}$, $\pi(2p_{1/2})^{-1}$ and $\pi(1g_{9/2})^1$ states, respectively. Some of the higher-energy negative-parity states could represent a coupling of the above single-hole states and the first 2^+ level in ^{88}Kr . In particular, if the 576.96-keV $1/2^-$, 585.80-keV $5/2^- (3/2^-)$, 930.95-keV $7/2^-$, and 1324.28-keV $3/2^- (5/2^-)$ levels are a coupling of the $2p_{3/2}$ ground state and the 2^+ level, a weighted average of the energies of these levels should be about 775 keV, the energy of the first 2^+ level in ^{88}Kr . The weighted average of the energies of the four levels mentioned above is 874 keV. The weighted average energy of the states which might be formed by a similar coupling of the $1f_{5/2}$ second excited state to the first 2^+ level in ^{88}Kr should be about 220 keV above the weighted average energy of the states formed by coupling the $2p_{3/2}$ ground state to the first 2^+ level in ^{88}Kr . Assuming that the 867.08-keV $1/2^-$, 997.35-keV $7/2^-$, 1339.9-keV $3/2^- (5/2^-)$, 1488.13-keV $9/2^-$ and 1530.04-keV $3/2^-$ levels are formed by coupling the $1f_{5/2}$ state to the first 2^+ level in ^{88}Kr , the difference found between the weighted average energy of these levels and that of the $2p_{3/2}$ and 2^+ coupling is 426 keV. The two lowest-energy positive-parity levels in the ^{89}Rb level scheme are the 1195.2-keV $9/2^+$ and 1693.70-keV $5/2^+$ levels,

with the 2598.1-keV $3/2^+$ and 2866.2-keV $5/2^+$ levels considerably higher in energy. The 1693.70-keV level could be accounted for by the $1g_{9/2}$ particle state being coupled to the first 2^+ core vibrations of ^{88}Kr . The sudden appearance of a large number of low-spin, positive-parity states above 3.3 MeV may indicate that the odd proton has been promoted to the next major shell where the $2d_{5/2}$, $3s_{1/2}$, $2d_{3/2}$, and $1g_{7/2}$ subshells are available, or may indicate a possible coupling of the low-lying negative-parity proton hole states to the 3^- vibration of ^{88}Sr or ^{90}Sr according to the particle-core coupling scheme discussed for the levels of ^{89}Sr .

The uses of particle-plus-quadrupole and anharmonic vibrator models as a theoretical tool for the study of ^{89}Rb are not precluded by any of the levels seen in this work and comparison of the ^{89}Rb level scheme with the Coriolis coupling model would require a detailed calculation since a "feel" for how the various couplings and band mixings occur is not readily obtainable. It is doubtful if model comparisons can provide a choice between possible descriptions without more firm J^π assignments in ^{89}Rb .

An examination of the ^{89}Rb level scheme shows that a number of inconsistencies exist in the spin assignments and transitions seen, as exemplified by the strong transition between the 1693.70-keV $5/2^+$ level and the 576.96-keV $1/2^-$ level. This particular problem could be accounted for by three possibilities: (1) the transition in question is misplaced, (2) the J^π assignments to one or both of these levels may be in error, or (3) a model calculation may account for the enhanced transition. Confidence in the present work rules out possibility (1). As has been noted

several times, the J^π assignments for this decay may be questionable and it is possible that some of them are wrong. Possibility (3) is supported by Scholz and Malik (81), who note that the Coriolis coupling model can cause some electromagnetic radiations to be enhanced or inhibited when compared to single-particle predictions.

E. Conclusions

In this work the decays of ^{89}Kr and ^{89}Rb have been studied and level schemes proposed for ^{89}Rb and ^{89}Sr . The main levels of ^{89}Sr have been established in the past through reaction work and earlier spectroscopy. The present experiment not only confirms much of the reaction and spectroscopy data, but in several cases proposes new J^π assignments and level interpretations and expands the picture of the structure of ^{89}Sr as illuminated in the decay of ^{89}Rb . These improvements to the ^{89}Sr level structure picture could serve as a basis for further theoretical study. Experimentally, further spectroscopy, particularly gamma-gamma coincidence studies with greater statistics, might lead to the observation of some of the weak but expected transitions not seen in this work. However, further study would probably not change the results of the present work to any significant extent.

The lack of supporting reaction data, from which it is possible to resolve structure ambiguities, is obvious in the discussion of the ^{89}Rb level scheme. The current work provides ample gamma singles and coincidence information, but many ambiguities remain in the discussion of the level spin and parity assignments which need supplementary information to be clarified. Detailed comparison with model predictions will probably be

Inconclusive without firm J^π assignments. The systematic study of ^{89}Kr and ^{89}Rb decays in this work establishes a beta branch of 14% to the ground state of ^{89}Rb , and the absence of beta feeding to the 220.90-keV first excited level in ^{89}Rb strongly supports the preliminary Q_β value of 4.878 ± 0.049 MeV communicated by Clifford (45).

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