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Decay of ^{77}Sr and level structure of ^{77}Rb

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An oil vapor helium-jet transfer system was used to study the β^+ decay of ^{77}Sr produced in the ^{40}Ca(^{40}Ca,2pn)^{77}Sr reaction at 110–130 MeV. Singles and coincidence measurements established the decay to four levels in ^{77}Rb and allowed measurements of $T_{1/2}=9.0\pm0.2$ sec for the decay half-life and $Q_{EC}=6986\pm227$ keV for the total decay energy. In-beam studies of the ^{40}Ca(^{40}Ca,3pγ)^{77}Rb reaction were made at 117 MeV. Two distinct bands were observed in ^{77}Rb and probable spin and parity assignments were made. These data favor $J^\pi=\frac{5}{2}^+$ for the ^{77}Sr ground state. The ^{77}Rb bands are compared to neighboring odd-A nuclei and to recent calculations.

[RADIOACTIVITY ^{77}Sr [from ^{40}Ca(^{40}Ca,2pn)], $E=110$–130 MeV. Measured $T_{1/2}$, $\sigma(E)$, E_γ, E_β, I_β, γ-γ, x-γ, and β-γ coincidences, deduced levels, Q_{EC}, logft. He jet, Ge(Li), Ge, and plastic detectors.
NUCLEAR REACTIONS ^{40}Ca(^{40}Ca,3pγ)^{77}Rb, $E=117$ MeV. Measured E_γ, I_γ, $\sigma(\theta)$, p-γ, and γ-γ coincidences. Deduced levels, branching ratios, J^π, δ. Ge(Li) detectors. Enriched target. Comparison with systematic trends and calculations.]

I. INTRODUCTION

Experimental studies of electromagnetic and beta decays of states in isotopes far from stability continue to provide diverse and sensitive tests of current nuclear models. For example, the measurement of nuclear masses and electric moments can be used to test theoretical predictions of macroscopic properties such as shape and binding energy derived from potential energy surface models,[1] while detailed examination of the excited level sequence in these nuclei can be used to test differing microscopic models of the residual nuclear interaction.[2–4]

Nuclei in the region near $N=Z=40$, where a transition from sphericity to deformation occurs,[5] provide a particularly rich testing ground for models. The most bound nuclear shape is sensitive to the number of neutrons and protons, and depends also on the residual interactions between nucleons. Light Rb and Kr isotopes have been reported to be triaxial,[3,6] Sr isotopes to be prolate,[5] and Y isotopes to be slightly oblate,[7] while for several nuclei in this region there is evidence of shape coexistence.[8] At present, data on many nuclei are missing and a systematic picture of this transitional region has not yet emerged. However, new experimental methods are evolving[9,10] which should allow detailed investigation to be completed.

The complementary nature of prompt γ-ray spectroscopy and radioactive decay experiments should be emphasized in nuclear structure research far from stability. Combining "in-beam" and radioactive decay data is especially important in experiments on odd-A and odd-odd nuclei where ground state spins and parities are unknown, and where nuclear isomerism is common. Isotopes such as ^{77}Rb can be produced only in a few heavy ion reactions and prompt spectroscopy is limited to the yrast and near yrast high spin cascades. In contrast, radioactive decay populates lower spin levels which have structure similar to their parent and may lie well above the yrast region. Only when these data are combined can a full picture of the ground state properties and modes of excitation be constructed, thus allowing unambiguous tests of nuclear models.

At the onset of this work, ^{77}Rb had been observed only in radioactive decay[11] and atomic beam experiments.[12,13] Its ground state spin and electromagnetic moments had been extracted, and indicated ^{77}Rb to be one of the most deformed nuclei known.[13] A dynamical verification of this, through the observation of rotational bands, seemed desirable. No excited levels had been previously reported for ^{77}Rb, although three γ rays had been seen[14] in the decay of ^{77}Sr.

II. EXPERIMENTAL METHOD

A. Helium-jet studies

The ^{40}Ca(^{40}Ca,2pn) reaction was used to produce ^{77}Sr. Rolled natural calcium foils of 2.4 mg/cm^2 thickness were bombarded with 140—170 MeV beams from the BNL tandem Van de Graaff facility. The ^{40}Ca beam entered a helium-filled bombardment cell through a 4 mg/cm^2 Ta entrance window, losing about 30 MeV in the process, before striking the target mounted adjacent to the window. The recoiling isotopes were thermalized and transported to a low background environment by a He-jet system which has been described previously.[15,7] It was found that the isopentyl alcohol/water carrier vapor employed previously destroyed the calcium targets through oxidation, so a heated oil-vapor system was developed. The helium gas supply at 1.2 atm was contrained to pass within 0.5 cm of an oil bath maintained at 120 °C. The vapor thus produced was an efficient carrier and protected the target by forming a thin oil covering. No deterioration of the target was observed during runs lasting several days. The activity carried by the He-jet system was collected on a Mylar tape which periodically was advanced to the counting station by program control.

A rigorous assignment of gamma transitions from levels in ^{77}Rb was made in a prompt particle-gamma coincidence experiment (see Sec. II B 1). The observation of some of these transitions in radioactive decay confirmed the observation of ^{77}Sr.

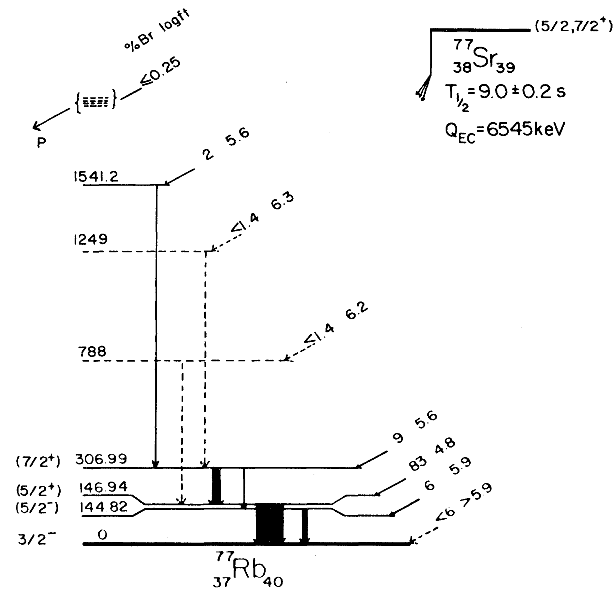

FIG. 1. Radioactive decay scheme established for ^{77}Sr.

1. Coincidence measurements

The decay scheme of levels in ^{77}Rb was established from a γ-γ coincidence experiment. A planar Ge detector was used to detect low energy (10—500 keV) γ rays and x rays, and a Ge(Li) detector used for higher energy transitions. ^{77}Sr sources were prepared for 10 sec and then transferred to a position between the detectors for counting for 10 sec. Four-parameter data were collected: two transition energies, time of coincidence after transfer, and time between photon detections.

The decay scheme constructed from these data is shown in Fig. 1, and details of γ-ray energies, intensities, and β^+ branching are given in Table I. Levels at 788 and 1249 keV were populated only weakly and were not shown definitively to exist in ^{77}Rb. A search was made for level lifetimes in the range $10 < T_{1/2} < 100$ nsec using the γ-γ timing information. No evidence was found for any state having a lifetime longer than $T_{1/2} > 8$ nsec.

2. Half-life measurements

It has been previously observed that ^{77}Sr is a β^+-delayed proton emitter[14] with a half-life of $T_{1/2} = 9 \pm 1$ sec. Three γ rays were reported to decay with the same half-life and were thus assigned to $^{77}\mathrm{Sr}(\beta^+) \rightarrow {}^{77}\mathrm{Rb}$. In the present study five γ rays were firmly assigned to ^{77}Rb, and probably two more. Four of the gammas were sufficiently strong to permit lifetime extraction. The strongest, at 146.9 keV, was found to be a doublet, unresolved from a transition in the subsequent $^{77}\mathrm{Kr} \rightarrow {}^{77}\mathrm{Br}$ daughter decay, so a two-component analysis of this decay was required. Following a 10 sec irradiation, a count cycle of 51 sec was used and data were routed into eight time bins to follow the decay. Detector count rates were limited to < 800 cps which kept the analog-to-digital converter (ADC) deadtime correction to $< 1\%$. A weighted average value of $T_{1/2} = 9.0 \pm 0.2$ sec was adopted for ^{77}Sr.

TABLE I. A compilation of measurements on the decay of ^{77}Sr to states in ^{77}Rb. Gamma and total intensities are in percent and normalized to 100 units decaying to the ground state. Energies are in keV. Uncertainties are shown in parentheses.

E_{lev} (keV)	E_γ[a] (keV)	E_γ[b] (keV)	I_γ	I_{tot}	Positron branching Ratio 0% g.s.b.	Positron branching Ratio 6% g.s.b.	logft 0% g.s.b.	logft 6% g.s.b.
0						6		5.90
144.82(3)	144.82(3)	144.75(10)	7.3(4)	7.5(4)	5.7(4)	5.5(4)	5.90(5)	5.92(5)
146.94(2)	146.94(2)	146.87(10)	92.6(2.1)	92.5(2.0)	82.9(2.0)	77.7(2.0)	4.83(1)	4.84(1)
307.02(3)	160.10(3)	159.90(10)	9.9(5)	9.6(5)	8.9(5)	8.4(5)	5.60(3)	5.62(3)
	162.11(12)		1.8(2)	1.8(2)				
(788)	641.2(2.5)		< 1.4	< 1.4	< 1.2	< 1.1	> 6.2	> 6.2
(1249)	942.0(3.0)		< 1.3	< 1.3	< 1.3	< 1.3	> 6.3	> 6.3
1541.2	1234.2(5)		2.6(6)	2.5(6)	2.5(6)	2.4(6)	5.65(11)	5.69(11)

[a]Present results.
[b]Reference 14.

3. *Mass measurement*

The $^{77}Sr \rightarrow ^{77}Rb$ decay energy (Q_{EC}) was measured in a β^+,γ coincidence experiment. Positrons were detected in a $\Delta E + E$ plastic scintillator telescope which viewed the activity on the transport tape through a thin Mylar window. Coincident gamma rays were detected in a Ge(Li) detector of 22% relative efficiency positioned at 180° to the telescope. The telescope consisted of a 1 mm thick, 25 mm diameter ΔE element of NE102 scintillator coupled by a light pipe to a photomultiplier tube, followed by an E detector (also NE102) of 150 mm thickness and 127 mm diameter. A Pb collimator was positioned between ΔE and E detectors in order to ensure that all positrons and photons entering the E counter had traversed the ΔE detector. The thin ΔE detector substantially reduced the gamma-ray response of the telescope, especially for 511 keV annihilation photons. A triple coincidence ($\Delta E, E, \gamma$) was required for positron registration. The thick E counter alone served to measure the positron energy.

Calibration of the positron telescope was accomplished in several complementary ways. Sources of ^{58}Cu produced in the ^{58}Ni(p,n)^{58}Cu reaction were collected with the He-jet system. The gain of the E detector electronics was adjusted so that the end point of this decay ($E = 7500$ keV) was 25% below pulse height saturation. A second (p,n) calibration was obtained for ^{27}Al(p,n)^{27}Si. Additional internal calibrations were obtained from the decay of several *fp*-shell nuclei such as ^{49}Cr, ^{50}Mn, ^{52}Fe, and ^{54}Co, which were formed from reactions of the ^{40}Ca beam with ^{16}O from the slightly oxidized target, from ^{12}C in the oil vapor, and in a calibration run using ^{14}N as the carrier gas in place of He.

Positron spectra in coincidence with gamma rays from levels populated directly in the decay were projected from "off-line" sorting of the data tapes. Positron end points were determined by extrapolating the slope of a Fermi-Kurie plot of the data. To minimize the effects of scattering and pileup, it was found that the best reproducibility was obtained using a linear fit to the region of the spectrum from 40 to 90 percent of the maximum energy. In addition, shape fitting analysis[7] was employed for an independent check of the Fermi-Kurie results. The two methods of analysis gave consistent results within experimental errors.

Measurement of the ^{77}Sr positron energy required the $\Delta E,E$ telescope with a thick E detector. This was necessitated by the high energy of the positrons (nearly 6 MeV) in the ^{77}Sr decay and ^{58}Cu calibration. In addition to the ^{77}Sr measurement, a separate experiment was performed for the determination of the decay energies of ^{76}Rb and ^{77}Rb. These lower energy end points were successfully measured with a simpler positron detection scheme without a ΔE element and a 50 mm by 64 mm E counter. Decay energies for ^{76,77}Rb were found to be in agreement with other recent measurements. Tables II and III summarize all of these measurements, both for the isotopes under study and for the calibration standards.

B. In-beam studies

Levels in ^{77}Rb were populated in the ^{40}Ca(^{40}Ca,3pγ)^{77}Rb reaction at 117 MeV. A 0.86 mg/cm^2 thick target enriched in ^{40}Ca (>99%) on a 16 mg/cm^2 thick Pb backing was used.

1. *Coincidence measurements*

An independent confirmation of the isotopic origin of γ rays from the ^{40}Ca+^{40}Ca reaction was made in a particle-gamma coincidence study. A silicon surface-barrier $E,\Delta E$ telescope with 980 and 50 μm thick detectors subtending 400 msr was placed at 0° to detect light charged particles. Gamma rays were detected in 18% and 22% efficient Ge(Li) detectors placed at ±125° to the beam direction, while neutrons were detected in an array of NE213 scintillators placed around 0°. Peak loci arising from protons, deuterons, and alphas were resolved in the telescope $E,\Delta E$ map, as were peaks arising from several coincident charged particles (2p, 3p, αp, etc.) simultaneously entering the telescope. "On-line" windows were set on all those features and coincident γ-ray spectra were accumulated. An example of such data is shown in Fig. 2. In this figure the ratio of photopeak intensities in spectra gated by p and 2p coincidences is shown. This ratio has been found in other experiments to be a clear measurement of proton multiplicity, and indicates that the lines of interest are all associated with three proton evaporation. Further, these lines were found not to be in coincidence with either neutrons or alpha particles, so the reaction channel was established. At the same time, γ-γ-t coincidences were collected and stored on tape for "off-line"

TABLE II. The positron end points used in the calibration of the plastic detector used in the β^+-γ coincidence study. Energies are in keV.

Nucleus	Gamma transition gate	E_{β^+} Fit	E_{β^+} Standard	ΔE
^{49}Cr	153	1517	1453	+64
^{49}Cr	91	1540	1515	+25
^{53}Fe	377	2319	2343	−24
^{42}Sc	437 + 1228 + 1524	2823	2870	−47
^{50}Mn^m	1443	3470	3513	−43
^{52}Fe^m	622 + 870 + 929	4404	4353	+51
^{54}Co^m	1129 + 1407	4445	4469	−24

TABLE III. Details of mass measurements made for ^{76,77}Rb and ^{77}Sr observed following the ^{40}Ca+^{nat}Ca reaction. All energies are in keV. Numbers in parentheses are the combined statistical and calibration errors.

Nucleus	Gamma transition gate	E_{β^+}	Q_{EC}	Q_{EC} Adopted	Q_{EC} Previous
	425	4475(174)	8068(175)		
^{76}Rb				8094(162)	8063(44)[a]
	2570	4661(436)	8254(440)		
	648	3759(233)	5495(235)		
^{77}Rb	393	3649(93)	5131(95)	5113(69)	5272(26)[b]
	245	3668(149)	4935(150)		
	179	3835(96)	5102(98)		
	147	5848(286)	7017(286)		
^{77}Sr				6986(227)	7197(287)[c]
	160	5605(376)	6934(376)		

[a]Reference 16.
[b]Reference 17.
[c]Reference 14.

analysis. The decay scheme deduced from these data shows two distinct bands of coincident transitions, which are illustrated in Fig. 3.

In ^{77}Rb the $\frac{9}{2}^+ \rightarrow \frac{7}{2}^+$ decay of 25 keV was not observed directly, but was inferred from the γ-γ coincidence data, where a window set on the 160 keV $\frac{7}{2}^+ \rightarrow \frac{5}{2}^+$ transition showed the 502-742-946 cascade in coincidence. The branching ratio given in Table IV was calculated assuming an intensity balance through the $J^\pi = \frac{7}{2}^+$ level; that is, that there is no side feeding.

2. Angular distribution measurements

To provide more information on the bands observed in the coincidence studies, γ-ray angular distributions were measured. Data were collected at 0°, 90°, 118°, 132°, and

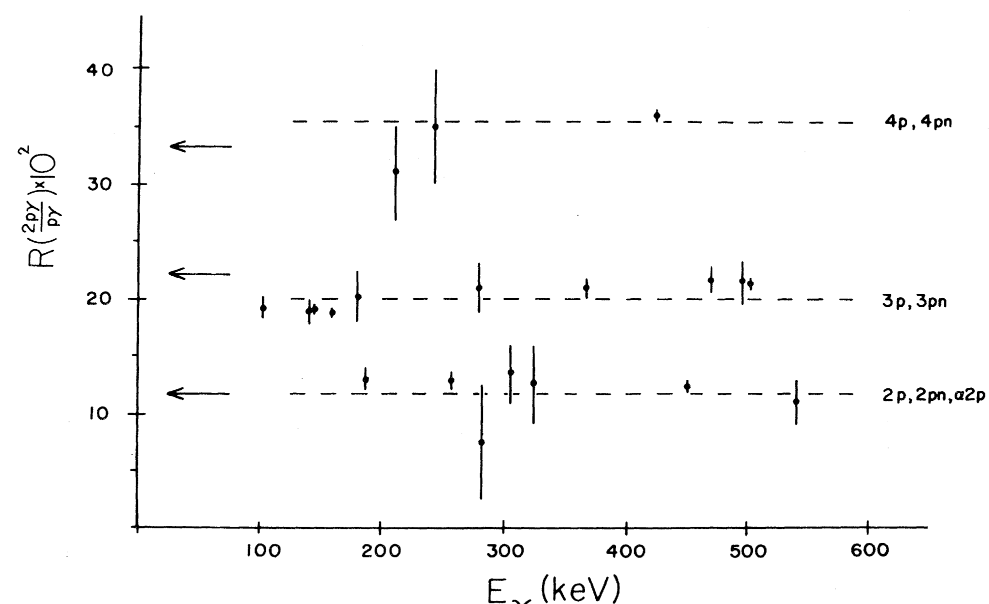

FIG. 2. A plot of the ratio of photopeak intensities in gamma ray spectra gated by one and two protons, respectively. Groups of lines known to belong to two and four proton evaporation channels have distinctly different ratios to the ^{76,77}Rb(3pn,3p) transitions. The arrows on the left are the ratios for two, three, and four proton evaporation channels calculated assuming the proton energy spectrum was not channel dependent.

144° with respect to the beam direction. The beam was chopped in a 10 sec "on," 1 sec "off" cycle with prompt and delayed γ rays routed into separate spectra. With suitable normalization these data could be used to form a "prompt-only" spectrum, with radioactivity subtracted. These corrected data were needed for estimating the degree of nuclear alignment produced in the ^{40}Ca+^{40}Ca reaction. The relative normalization of data acquired at each angle was made using the integrated beam charge deposited on the target.

The γ-ray intensities were fitted to second and fourth order Legendre polynomial expansions. Known pure $E2$ decays in α2p and 4p reaction channels were used to estimate the degree of alignment following the formalism of Yamazaki.[18] The strong 185-502-742 and 368-575-772 cascades in ^{77}Rb were found to have very similar alignment, and conservative limits of alignment as a function of spin were established. Using these data, it was possible to make estimates of the degree of multipole mixing involved in several $\Delta J=1$ transitions observed in ^{77}Rb. This procedure, based on the assumption that heavy-ion reactions yield predominantly $J\rightarrow(J-L)$ "stretched" γ cascades, does not rigorously define a spin sequence, but provides a probable set of assignments. The existence of interlocking decays with stopover and crossover branches was important in excluding other spin sequences. Table IV gives gamma ray energies, intensities, angular distribution coefficients, and branching ratios. Parity assignments are discussed in the next section.

III. RESULTS AND DISCUSSION

An understanding of the radioactive decay of ^{77}Sr is made easier if the properties of excited levels in ^{77}Rb are initially established. Consequently, we discuss the "in-beam" studies first, then concentrate on the radioactivity measurements.

A. Band structure of ^{77}Rb

The ground state of ^{77}Rb has been extensively studied in atomic beam experiments.[12,13] It is known to have spin

TABLE IV. Gamma ray properties deduced from the "in-beam" study of ^{77}Rb. Gamma ray energies are in keV; errors are in parentheses.

E_{level}	E_{gamma}	I_γ[a]	a_2	a_4	Br	$J_i^\pi \rightarrow J_f^\pi$[b]	Multipolarity	δ
				Positive parity band				
146.94(2)	146.94(2)	56.5	−0.22(2)	0.0(2)	100	$(\frac{5}{2}^+)\rightarrow\frac{3}{2}^-$	$E1$	$\lvert\delta\rvert<0.03$
307.02(3)	160.10(3)	22.3	+0.23(1)	+0.02(1)	83(1)	$(\frac{7}{2}^+)\rightarrow(\frac{5}{2}^+)$	$E2/M1$	+0.39(6)
	162.11(13)	4.4	−0.24(2)	0.00(2)	17(1)	$(\frac{7}{2}^-)\rightarrow(\frac{5}{2}^-)$	$E1$	$\lvert\delta\rvert<0.03$
331.80(9)	24.78[c]				46(2)	$(\frac{9}{2}^+)\rightarrow(\frac{7}{2}^+)$	$E2/M1$	
	184.86(8)	26.5	+0.33(2)	−0.12(2)	54(2)	$(\frac{9}{2}^+)\rightarrow(\frac{5}{2}^+)$	$E2$	
804.14(11)	472.23(13)	3.8	+0.32(1)	+0.06(2)	49(2)	$(\frac{11}{2}^+)\rightarrow(\frac{9}{2}^+)$	$E2/M1$	+0.40(10)
	497.23(15)	4.0	+0.33(5)	−0.13(5)	51(2)	$(\frac{11}{2}^+)\rightarrow(\frac{7}{2}^+)$	$E2$	
833.51(17)	501.81(15)	26.6	+0.37(2)	−0.15(2)	100(5)	$(\frac{13}{2}^+)\rightarrow(\frac{9}{2}^+)$	$E2$	
1576(2)	742(2)[d]	11.5	(+)			$(\frac{17}{2}^+)\rightarrow(\frac{13}{2}^+)$	$(E2)$	
2522(5)	946(5)	5.0	(+)			$(\frac{21}{2}^+)\rightarrow(\frac{17}{2}^+)$	$(E2)$	
				Negative parity band				
144.82(3)	144.82(3)	33.8	−0.40(3)	+0.10(3)	100	$(\frac{5}{2}^-)\rightarrow\frac{3}{2}^-$	$E2/M1$	−1.8(5)
368.13(7)	223.31(9)	3.6	−0.40(3)	+0.10(3)	27(2)	$(\frac{7}{2}^-)\rightarrow(\frac{5}{2}^-)$	$E2/M1$	−1.8(7)
	368.14(9)	9.8	+0.37(2)	−0.16(2)	73(2)	$(\frac{7}{2}^-)\rightarrow(\frac{3}{2}^-)$	$E2$	
614.57(9)	246.51(9)	1.6	−0.50(5)	+0.05(5)	11(4)	$(\frac{9}{2}^-)\rightarrow(\frac{7}{2}^-)$	$E2/M1$	−1.0(1)
	469.88(13)	13.0	+0.31(2)	−0.12(2)	89(4)	$(\frac{9}{2}^-)\rightarrow(\frac{5}{2}^-)$	$E2$	
942.67(20)	328.00(50)	0.4	(−)		5(5)	$(\frac{11}{2}^-)\rightarrow(\frac{9}{2}^-)$	$(E2/M1)$	
	574.50(18)	7.0	+0.35(5)	−0.10(5)	95(5)	$(\frac{11}{2}^-)\rightarrow(\frac{7}{2}^-)$	$E2$	
1280(1)	665(1)[d]	5.0	(+)		>95	$(\frac{13}{2}^-)\rightarrow(\frac{9}{2}^-)$	$(E2)$	
1715(3)	772(3)	5.0	(+)		>95	$(\frac{15}{2}^-)\rightarrow(\frac{11}{2}^-)$	$(E2)$	

[a]Intensity normalized so total γ-ray flux to ground state is 100 units.
[b]Spin and parity assignments are discussed in the text.
[c]This low energy transition was not observed directly, but its presence was firmly established from the γ-γ data.
[d]Higher members of the bands were Doppler shifted and broadened which prevented precision measurements.

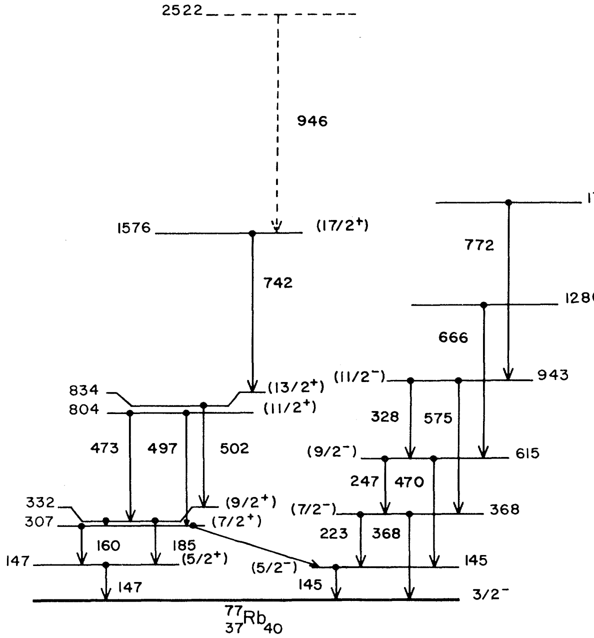

FIG. 3. Bands of states observed in ^{77}Rb following the ^{40}Ca(^{40}Ca,3pγ)^{77}Rb reaction at 117 MeV.

$I=\frac{3}{2}$, magnetic moment $\mu=0.655(3)$, and a large quadrupole deformation estimated at $\beta_2=0.45$. The $T_{1/2}=3.9$ min radioactive decay to ^{77}Kr has been found to proceed mainly by transitions to negative parity states with $\log ft$ values typical for allowed β decays observed in this mass region.[22] Consequently, a $J^\pi=\frac{3}{2}^-$ assignment can be made for the ^{77}Rb ground state. This assignment is firmly supported by a Nilsson model calculation which exactly reproduces the measured magnetic moment if the valence proton is assumed to be occupying the $\frac{3}{2}^- \mid 312\rangle$ Nilsson orbit.

In the present work, two bands of excited states were observed with distinctly different character. One band is based on the ground state and has a quite smoothly increasing level spacing with a regular sequence of crossover and stopover decays. The other band is based on the 149 keV level and is very staggered, with $J=\frac{7}{2},\frac{9}{2}$ and $\frac{11}{2},\frac{13}{2}$ members appearing in very closely spaced doublets. The duality of smooth and staggered bands is a rather common feature in this mass region, both for odd-N and odd-Z nuclei, with positive parity bands showing large irregularities. This behavior has been examined in detail by Kriener *et al.*,[19,20] who attribute the sharp staggering to the large Coriolis interaction on valence nucleons in the partially filled $1g_{9/2}$ shell. Thus, we may expect the staggered band in ^{77}Rb to have positive parity, as is observed in the adjacent odd-Z isotope ^{79}Rb and isotone ^{75}Br.

1. Positive parity band

The γ decay of the 149 keV bandhead provides further evidence favoring positive parity for this band. The 149 keV decay to the $J^\pi=\frac{3}{2}^-$ ground state has an angular distribution characteristic of a pure dipole decay ($\Delta J=1$) with no quadrupole mixing. A decay with $\delta(M2/E1)\approx 0$ is usually seen in parity changing decays ($\Delta\pi=1$) where electric dipole ($E1$) decay dominates the competition with magnetic quadrupole ($M2$) transitions. In contrast, other $\Delta J=1$ decays in this nucleus have significant dipole-quadrupole mixing, $\delta(E2/M1)\neq 0$, which may be expected from non-parity-changing ($\Delta\pi=0$) transitions where magnetic dipole and electric quadrupole decays compete freely.

The Coriolis-staggered level sequence has been calculated as a function of deformation by Kreiner.[20] In that calculation, the $\frac{7}{2}^+$ level is predicted to lie below the $\frac{9}{2}^+$ state for deformations in excess of $\beta_2=0.41$, while the $\frac{11}{2}^+$ and $\frac{13}{2}^+$ members exchange order at $\beta_2=0.42$. At this large deformation, the lowest positive parity state is predicted to have $J^\pi=\frac{5}{2}^+$. The sequence of levels we observe in ^{77}Rb reveals the $J^\pi=\frac{7}{2}^+$ state 25 keV below the $J^\pi=\frac{9}{2}^+$ state, and the $J^\pi=\frac{11}{2}^+$ state 29 keV below the $\frac{13}{2}^+$ state. Thus, we may expect $\beta_2\approx 0.42$ or $\epsilon_2\approx 0.40$.

A similar level inversion has been observed by Panqueva *et al.*[3] in ^{79}Rb. Using a triaxial rotor model, they also conclude that the level sequence and $B(E2)$ values indicate $\beta_2=0.42$. This quadrupole deformation is in good agreement with the prediction of $\epsilon_2=0.35$ and $\epsilon_4=0.05$ predicted by the potential energy surface calculations of Möller and Nix.[1]

Positive parity bands of this nature have been observed in several odd-Z nuclei in this region. A comparison of these staggered bands in ^{79,81}Rb and ^{75}Br to the ^{77}Rb band is shown in Fig. 4. It can be seen that all the positive parity bands are staggered, but only in ^{77,79}Rb is the staggering large enough to cause inversion of the level sequence.

The positive parity bands in $^{79-85}$Rb have been investigated by Panqueva *et al.*[3] Many $B(E2)$ values have been extracted from these bands. Calculations of level sequence have been performed within the framework of the IBA-1 and IBA-2 models, and in the triaxial rotor model. All of these models can fit the observed level sequences (the triaxial rotor model having $\gamma\approx 26°$), but predict considerably different $B(E2)$ values. Lifetime measurements for ^{77}Rb will be instructive in continuing these systematic model tests. Of particular interest is the question of whether triaxiality persists through the transitional region to the deformed $N\simeq Z\simeq 40$ nuclei. Measurements are planned and will be reported separately.

2. Negative parity band

The sequence of levels based on the ground state is characterized by rotational-like level spacing and the presence of stopover and crossover decay branches. The bandhead is known to have negative parity, and the large multipole mixing ratios observed for the $\Delta J=1$ transitions preclude any parity change. Similar bands have been observed in ^{79}Rb,^{79}Sr. A plot of the moment of inertia extracted for these negative parity bands is shown in Fig. 5, where it can be seen that all have a staggering, which is smallest for ^{77}Rb, and that the bands have an average moment of inertia which is close to that recently measured for even Sr isotopes.[5]

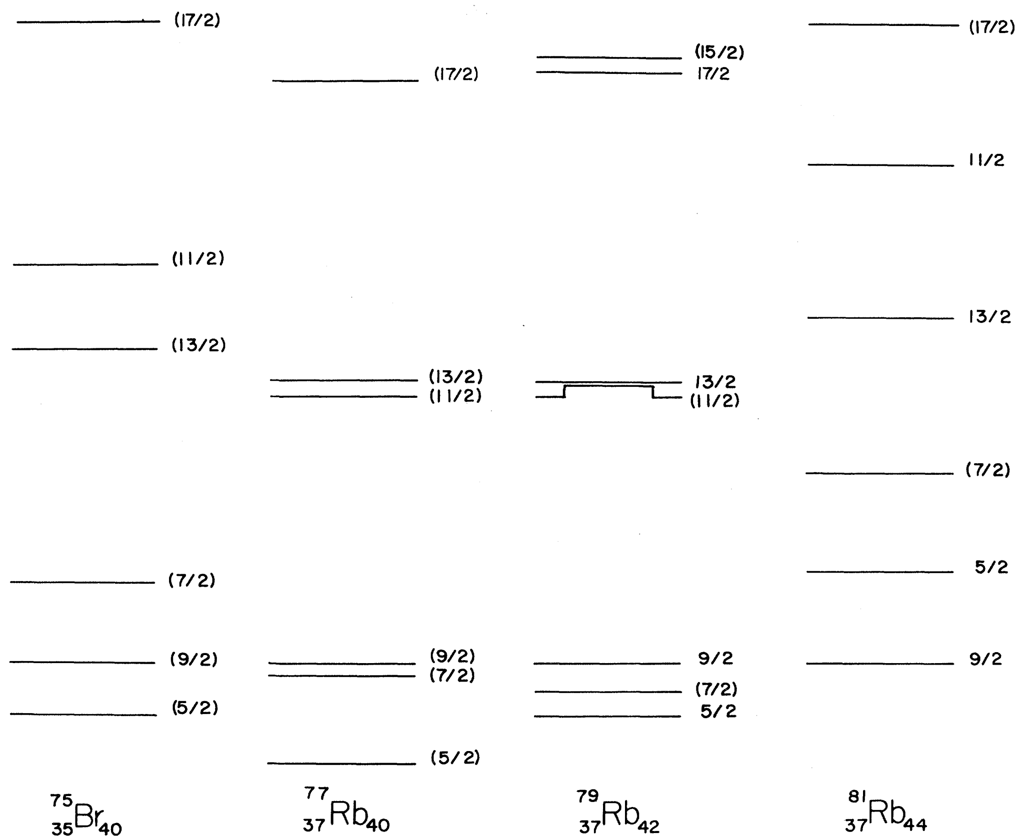

FIG. 4. Positive parity bands in ^{75}Br and ^{77,79,81}Rb. All these bands are perturbed, but only in the highly deformed ^{77,79}Rb nuclei is level inversion seen.

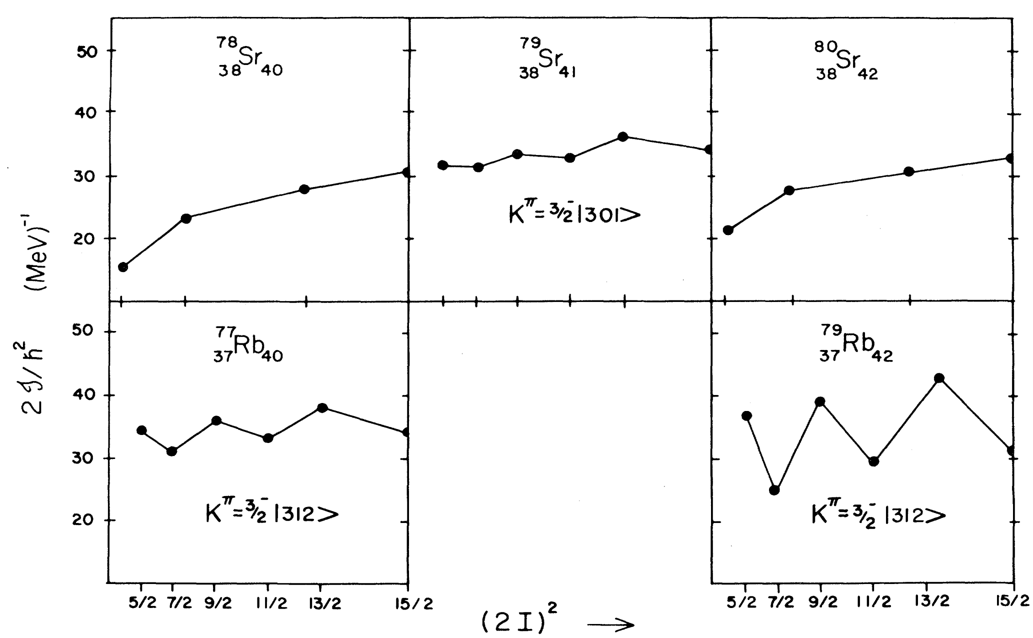

FIG. 5. The moment of inertia for negative parity bands in light Sr and Rb isotopes. $2\mathcal{J}/\hbar^2=2J/E$ in odd nuclei and $=(4J-2)/E$ in even. Data are taken from Refs. 3 and 5.

The data for ^{79}Rb come mainly from the Cologne group,[3] supplemented by data obtained at BNL using the $^{58}Ni(^{24}Mg,3p)^{79}Rb$ reaction at 85 MeV. Our BNL study confirmed the previous work, and provided candidates for the sequence of unfavored members of the negative parity band. Also, the original measurement[7] of a high degree of conversion ($\alpha_k = 4.1 \pm 0.3$) for the 39 keV decay of the $K = \frac{3}{2}$ bandhead in ^{79}Rb has been shown to be in error by a recent remeasurement,[21] which finds $\alpha_k = 1.54 \pm 0.07$, as expected for a $\frac{3}{2}^- \rightarrow \frac{5}{2}^+$ $E1$ transition.

The ground state magnetic moment of ^{77}Rb can be used together with the measured multipole mixing ratios to extract a nuclear quadrupole moment for this band. Values of $Q_0 = +(2.3 \pm 0.7)$ b and $Q_0 = +(2.2 \pm 0.9)$ b were extracted from the $\frac{5}{2}^- \rightarrow \frac{3}{2}^-$ and $\frac{7}{2}^- \rightarrow \frac{5}{2}^-$ decays. These values are slightly lower than the predictions of Möller and Nix,[1] who calculated $Q_0 = 3.0$ b.

This method of extracting quadrupole moments from multipole mixing ratios can also be applied to the positive parity band. However, as the magnetic moment of the bandhead has not been measured, a theoretical estimate is required. Within the framework of the Nilsson model, the $\frac{3}{2}^- \mid 312 \rangle$ ground state is calculated to have a rotational g factor of $g_K - g_R = -0.08$ for a deformation $\beta_2 = 0.3 - 0.4$ and using $(g_S)_{\text{eff}} = 0.7 (g_S)_{\text{free}}$ and $g_R = Z/A$. This compares well with the experimental value of $g_K - g_R = -0.075 \pm 0.01$. A similar approach predicts $g_K - g_R = +1.06$ for the $\frac{5}{2}^+ \mid 422 \rangle$ bandhead. With this g factor and the multipole mixing ratios given in Table IV, we extract values for the quadrupole moment of $Q_0 = +(9.3 \pm 1.5)$ b for $J^\pi = \frac{7}{2}^+ \rightarrow \frac{5}{2}^+$, and $Q_0 = +(5.2 \pm 1.3)$ b for $J^\pi = \frac{11}{2}^+ \rightarrow \frac{9}{2}^+$. Clearly, the strong perturbation of the level sequence in the positive parity bands is manifested in the transition strengths, and our estimates are only qualitatively correct.

B. Decay of ^{77}Sr

1. *Ground-state spin assignment*

Having established the spins and parities of levels in ^{77}Rb, it is now possible to place some limitations on the ground state spin and parity of ^{77}Sr.

The major decay branch to the $J^\pi = \frac{5}{2}^+$ state at 147 keV in ^{77}Rb is by an allowed decay[22] with $\log ft = 4.83$. Hence, the spin and parity of ^{77}Sr can be limited to $J^\pi = (\frac{3}{2}, \frac{5}{2}, \frac{7}{2})^+$. The presence of a decay branch to the ^{77}Rb $J^\pi = \frac{7}{2}^+$ level at 307 keV with $\log ft = 5.60$ precludes the possibility of $J^\pi = \frac{3}{2}^+$, and so, ^{77}Sr is further limited to $J^\pi = (\frac{5}{2}, \frac{7}{2})^+$. A calculation of the single-particle level sequence in a deformed Woods-Saxon potential[23] shows that ^{77}Sr ($N = 39$) is expected to have a $J^\pi = \frac{5}{2}^+$ ground state for prolate deformation with $\beta_2 > 0.29$. This state has the asymptotic quantum numbers $\frac{5}{2}^+ \mid 422 \rangle$ in the Nilsson formalism.

The decay of ^{77}Sr to the ^{77}Rb ground state is parity changing with $\Delta J = 1$ or 2. Beta decay systematics[22] limit $\log ft$ to > 5.9, which corresponds to a ground state decay branch of $< 6\%$. The decay branches and $\log ft$ values in Table I are calculated for the limiting cases of having either a 0% or 6% ground state branch.

2. *Mass measurement*

A determination of the mass of ^{77}Sr was made by Hardy *et al.*,[14] who observed the delayed proton spectrum and inferred a value of $Q_{EC} - B_p = 3850 \pm 200$ keV. This value can be combined with a recent estimate[24] of the proton binding energy, $B_p = 3347 \pm 195$ keV, to deduce $Q_{EC} = 7197 \pm 287$ keV. This decay mode is very weak ($< 0.25\%$) and the statistical analysis of the data is model dependent. The desirability of collecting proton–x-ray coincidence data to remove some of the uncertainties has been pointed out.[14] Our β-γ result of $Q_{EC} = 6986 \pm 227$ keV is in agreement with the delayed proton result within errors. As the determinations are by different methods, the possibility of systematic error is reduced. The weighted mean value of these two experimental values is $Q_{EC} = 7069 \pm 178$ keV. This result is compared to several theoretical estimates in Table V. It can be seen that the experimental value is lower than most calculated results, but a more precise determination is required to rigorously test the theoretical mass models.

TABLE V. A comparison of the experimentally determined ^{77}Sr-^{77}Rb mass difference Q_{EC} with several theoretical estimates. All energies are in MeV.

Experiment	a	b	c	d	e	f	g	h	i	j
7.069±0.178	6.87	7.11	7.40	7.91	8.10	7.61	7.38	7.33	8.09	7.27

[a]Reference 25.
[b]Reference 25.
[c]Reference 25.
[d]Reference 25.
[e]Reference 25.
[f]Reference 25.
[g]Reference 25.
[h]Reference 25.
[i]Reference 26.
[j]Reference 1.

IV. CONCLUSIONS

Excited bands of states have been observed for the first time in ^{77}Rb. These bands have rotational character, and the extracted moments of inertia are similar to bands in odd Sr isotopes. The in-band multipole mixing ratios are qualitatively reproduced by simple Nilsson model estimates. The deformation appears to be very large ($\epsilon_2 \approx 0.42$) but measurements of $B(E2)$ values are required to quantify this properly.

The spectroscopy of the positron decay of ^{77}Sr has been investigated. A restriction $J^{\pi}=(\frac{5}{2},\frac{7}{2})^{+}$ was established for the ^{77}Sr ground state, with positron branching ratios and Nilsson model calculations favoring the former assignment. A remeasurement of the ^{77}Sr-^{77}Rb mass difference was made which showed good agreement with the previous result.

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