Levels of ^{91}Rb and ^{91}Sr fed in the decays of ^{91}Kr and ^{91}Rb†

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Level schemes for ^{91}Rb and ^{91}Sr are proposed based on the study of the β decay of ^{91}Kr and ^{91}Rb, respectively. The samples were obtained using on-line mass-separation techniques applied to ^{235}U fission products. γ-, β-, and x-ray singles spectra, as well as (γ,γ) and (β,γ) coincidence spectra, were taken with Ge(Li) and Si(Li) detectors. Internal-conversion coefficients were determined for several transitions and the half-lives for the first two levels in ^{91}Rb and ^{91}Sr were measured. In view of the observed parity change between low-lying excited states and the ground state in ^{91}Rb the possibility of deformations to explain this level structure is discussed.

I. INTRODUCTION

The present paper is devoted to the levels of ^{91}Rb and ^{91}Sr populated in the β decay of 8.6-sec ^{91}Kr and 58-sec ^{91}Rb, obtained in the on-line separation of mass-91 uranium-fission products. These isotopes probably are placed on or near the border of a region where stable deformations have been predicted,[1] contained within the zone delimited by the closed shells $N=50$ and 82 and $Z=28$ and 50. This fact makes their study very interesting because transitional nuclei are usually not as well understood theoretically as spherical or clearly deformed ones.

The main γ rays following the decay of ^{91}Kr were first reported by Borg *et al.*[2] and by Amiel *et al.*,[3] as an example of the use of on-line techniques. Later, Eidens, Roekl, and Armbruster[4] published a level scheme with two transitions connecting three levels, and Mason and Johns[5] proposed another one with six transitions within five levels. However, both groups differed significantly regarding the Q value and β feedings. In the present work we propose a level scheme with 31 levels connected by 94 transitions, which carry 96% of the total observed γ intensity. The scheme is based on our results for (γ,γ) and (β,γ) coincidences, γ-ray energies and intensities, internal-conversion coefficients, the Q value, and the half-life for the first excited state. It corresponds to a ^{91}Rb structure impossible to understand within a spherical picture and deformations must be introduced in order to explain the parity change between low-lying excited states and the ground state.

Mason and Johns[5] also proposed a level scheme for ^{91}Sr, with 18 levels connected by 28 transitions; they gave neither $\log ft$ values nor spin-parity assignments, but measured a value for the half-life of the first excited level. Malmskog and McDonald[6] measured the half-life of the first excited state and the K/L conversion ratio for the deexciting transition. Macias-Marques[7] determined the Q value for the ^{91}Rb decay. In this paper we propose a level scheme on the same basis as for ^{91}Rb, which contains 39 transitions carrying 92% of the observed γ intensity within 16 levels, 10 of which coincide with excited ones previously reported in Ref. 5. Our experimental value for the half-life of the first excited state is in good agreement with those of Refs. 5 and 6.

The half-lives of the ^{91}Kr and ^{91}Rb ground states have been measured, and agree well with the results recently published by the group working at the TRISTAN project.[8]

II. EXPERIMENTAL PROCEDURES

A. On-line system for production and collection of samples

The samples used in these studies were produced in the Buenos Aires on-line facility (IALE project), which was described in detail in a previous paper.[9] Briefly, an uranyl-stearate target containing ~14 g of ^{235}U is placed in a thermal neutron flux of ~$5\times10^8\ n\,\text{cm}^{-2}\,\text{sec}^{-1}$; the rare gases produced in the ^{235}U fission are fed into the ion source of an electromagnetic mass separator and the mass-91 beam is received on an appropriate collector. No contaminations from other masses were observed.

B. γ-ray measurements

1. Singles γ-ray spectra

For these measurements the activity was collected on a movable aluminized Mylar tape.[9] This collector assembly was operated with different time schedules to vary the Kr-to-Rb activity ratio and thus allow a positive assignment for the detected radiations. Some of our spectra were recorded interposing a 0.8-mm Pb absorber in order to avoid the high counting rate generated by the low-energy part of the spectra.

A commercial Ge(Li) detector of 45 cm^3 and one produced in our laboratory having 65 cm^3, were used to record the γ spectra. When operated for short periods, and at an over-all gain of 0.33 keV/channel, the resolutions for the ^{60}Co γ rays were 3.0 and 6.0 keV, respectively. The detector pulses were fed through conventional electronics to a 4096-channel analyzing system provided with a small computer.

Energy calibrations were made using the lines of ^{57}Co decay[10] and the values given in Ref. 11 for the ^{60}Co, ^{88}Y, ^{192}Ir, and ^{203}Hg standards, as well as for the ^{56}Co and ^{66}Ga sources. The lines from the $^{1}H(n,\gamma)$ reaction[11] and the ^{16}N decay[12] were also used, as described in Ref. 13.

Efficiency calibrations over the range 0.13–3.3 MeV were performed collecting mass-138 activity on line, with exactly the same geometry as the one used for the mass-91 measurements, and recording the ^{138}Xe- and ^{138}Cs-decay lines. Since recently[14] we remeasured *off line* the relative intensities of these lines (and proposed them as secondary standards), every distortion due to the presence of activity at places away from the collector itself is automatically compensated for. Low- and high-energy extensions were done by measuring the ^{57}Co and ^{66}Ga standard sources[11] with a dummy carefully reproducing the on-line geometry. The resulting efficiency curve was defined within ±7% for the 0.2–2.5-MeV range, and within ±10% for the 0.05–0.2- and 2.5–5.0-MeV ranges. Spectra were analyzed either by hand, or by computer methods using the SAMPO[15] and ANAGAMMA[16] programs.

2. (γ,γ) coincidences

The two Ge(Li) detectors mentioned were also used for the (γ,γ) coincidence measurements. The large time spread of the pulses from the bigger detector made it impossible to go below 300 nsec in resolving time and thus fast coincidence electronics were not useful. A slow coincidence circuit with a resolving time of ~1 μsec was used, the random events being kept below 10% of the real coincidences by controlling the sample activity. The signals were processed by two 4096-channel analog-to-digital converters and both addresses generated stored on a magnetic-tape buffer. The data on this tape were later read back into the computer using a digital window placed at the position of the desired gating peak, and at least one additional window near this peak to subtract coincidences due to the Compton background. The coincidence spectra thus obtained were then further corrected for random coincidences.

3. Lifetimes

Ground-state half-lives were measured with the 45-cm^3 Ge(Li) detector using the multiscaling technique for the intense γ peaks of both decays studied. For the measurements corresponding to excited states we used a time-to-amplitude converter, with start pulses provided by a 7.6-cm × 7.6-cm NaI(Tl) detector, and the stop pulses by a 30-cm^3 Ge(Li) detector. The prompt resolving time was about 20 nsec; the time calibration was performed using standard delays.

C. Electron measurements

1. Internal-conversion electron spectra

The experimental setup and procedures for internal-conversion coefficient determinations have been described in detail in Ref. 17. In this work, a 3-cm^2 area, 3-mm depletion depth Si(Li) detector with a 4.5-keV resolution for the ^{137}Cs K line was used. The K-conversion coefficients for the 556-keV transition in ^{91}Y (Ref. 18), as well as the ones for the 304-keV transition in ^{85}Kr (Ref. 19) and the 151-keV transition in ^{85}Rb (Ref. 19), were used for calibration and normalization purposes.

2. Continuous β spectra and (β,γ) coincidences

A 1-cm^2 area and 15-mm depletion depth Si(Li) detector with 8-keV resolution for the ^{137}Cs K line was mounted into the same setup used for the conversion-electron measurements[17] and used to record continuous β spectra and to perform slow (β,γ) coincidences. An energy calibration up to 2.3 MeV was done determining directly from the experimental β spectra the end points of the spectral distributions of the ^{90}Sr, ^{137}Cs, and ^{197}Hg β decays, which could be defined to within about ±150 keV. This yielded a linear response curve which, when extrapolated to higher energies, gave a Q_β value for the ^{91}Rb decay which was in excellent agreement with the accurate 5.80 ± 0.09 MeV measured in Ref. 7 (Sec. III A 4). We thus expected that the rough end-point estimation method we used would be good enough to decide between the somewhat conflicting Q_β values published[4,5] for the ^{91}Kr decay (Sec. III B 4). The coincidence circuit, as well as the procedures to store and analyze the data, were the same as those discussed in Sec. II B 2.

D. X-ray measurements

The x rays and low-energy γ rays were observed with a 25-mm^2 area and 3-mm depletion depth Si(Li) x-ray detector, having a resolution of 290 eV for the $K\alpha$ x rays in Fe, placed in front of the moving-tape collector. Energy and efficiency calibrations were performed as described in detail in Ref. 20. From these measurements we obtained internal-conversion coefficients using the XPG (x-ray-peak-to-γ-peak) method.

No γ transitions with energy below 100 keV were detected, probably due to the high Compton background generated by the very intense 93.40- and 108.65-keV γ rays, as well as to the high-energy β rays, associated with the mass-91 activity.

III. EXPERIMENTAL RESULTS

A. ^{91}Kr decay

1. Singles γ spectra; (γ, γ) and (β, γ) coincidences

Figure 1 shows a typical γ spectrum taken with a 0.8-mm-thick Pb absorber. Here the ^{91}Kr activity is enhanced with respect to the ^{91}Rb one by an appropriate sequence for the moving-tape collection time and the measuring time. It was found that to allow a positive identification for the origin of the transitions through spectra comparison very high enhancements (~10^3) were not as useful as moderate ones (~30).

The results from several runs with and without Pb absorber are summarized in Table I. They are in general agreement with the scarce data previously reported[4,5] and also with the more extensive ones of Ref. 21 although our intensities are up to 30% higher than those given in the latter reference. We were able to assign 108 transitions to the ^{91}Kr decay; this assignment is doubtful in only four cases, which carry 0.9% of the total intensity. The (γ,γ) coincidence results are summarized in Table II. The (β,γ) coincidences gated by the γ rays of 108.65, 506.8, 613.05, 1108.80, and 1501.80 keV showed β branches of, respectively, 5.4 ± 0.3, 5.0 ± 0.3, 4.5 ± 0.3, 4.0 ± 0.3, and 4.0 ± 0.3 MeV in coincidence with them.

2. Lifetime determinations

The half-life for the ^{91}Kr ground-state decay was determined to be 8.6 ± 0.1 sec, in excellent agreement with Ref. 8. For excited states the only transition strong enough to allow a half-life measurement was the one of 108.65 keV. Our results for the level at that energy is $T_{1/2}< 20$ nsec, which, according to the empirical systematics of lower limits for $T_{1/2}$ values,[22] implies an $E1$, $M1$, or $E2$ character for the deexciting transition.

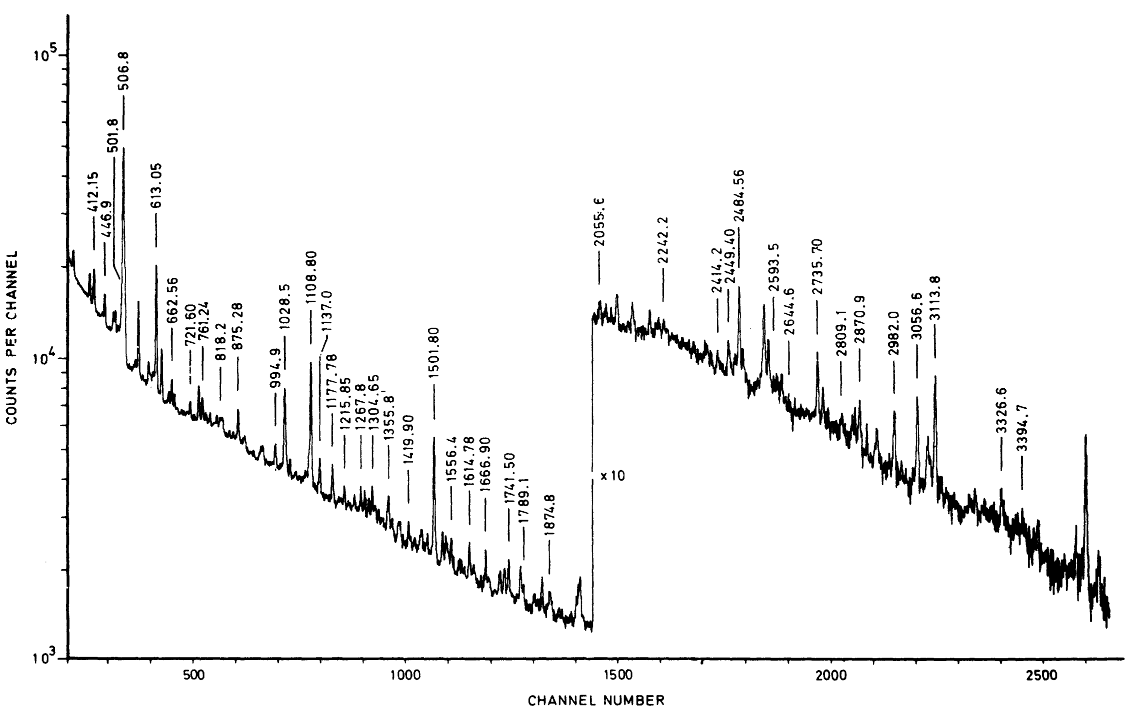

FIG. 1. Partial γ spectra with enhanced Kr activity taken by interposing a 0.8-mm-thick Pb absorber. Some of the Kr decay full-energy peaks are labeled with the corresponding energy value.

TABLE I. γ rays observed in the decay of ^{91}Kr.

Energy (keV)	Relative intensity [a]	Energy (keV)	Relative intensity [a]
108.65±0.10	1000 ±100	1371.4 ±0.8	2.3±1.1
196.0 ±0.5	4 ± 3	1387.7 ±0.8	15.2±1.7
398.23±0.21	33 ± 4	1392.5 ±0.5	17.0±1.7
412.15±0.17	48 ± 5	1419.90±0.24	18.1±2.3
446.9 ±0.3	34 ± 5	1439.0 ±0.6 [c]	5.7±1.6
475.1 ±0.3	17 ± 4	1455.7 ±1.2	10.0±2.5
481.26±0.21	21 ± 3	1479.75±0.22	13 ±3
489.9 ±0.5 [b,c]	5 ± 3	1501.80±0.14	151 ±16
501.8 ±0.4	40 ± 10	1528.45±0.20	25 ±3
506.8 ±0.3	400 ± 60	1541.0 ±1.0 [d]	8.8±2.3
546.4 ±0.3	12.7± 2.0	1548.9 ±1.0	9.0±2.2
569.1 ±0.7	3.1± 1.0	1556.4 ±1.2	26 ±5
588.55±0.18	17 ± 4	1582.3 ±0.9 [b,c]	8 ±4
613.05±0.10	150 ± 16	1614.78±0.24	32 ±6
630.22±0.21	41 ± 4	1666.90±0.18	28 ±3
662.56±0.15 [c]	23 ± 4	1674.7 ±1.3 [c]	3.1±1.6
671.45±0.18 [c]	12.0± 2.0	1677.4 ±0.5	3.1±1.6
711.1 ±0.5 [c]	3.5± 0.5	1727.8 ±0.5	3.1±2.4
715.1 ±0.5 [c]	3.4± 0.7	1741.50±0.25	12 ±6
721.60±0.14	13.1± 1.4	1789.1 ±0.3	11.9±2.5
761.24±0.14 [c]	20.3± 2.1	1874.8 ±0.5	15.4±1.6
771.9 ±0.5	5.2± 1.5	1881.0 ±1.3	9.6±2.0
785.25±0.22	7.1± 1.0	2055.6 ±0.4	9.8±2.5
797.1 ±0.5	2.0± 0.4	2072.6 ±0.4 [d]	6.9±1.6
800.0 ±0.5	1.4± 0.4	2242.2 ±0.4	10 ±3
806.71±0.23	7.3± 1.4	2252.2 ±0.8	6.6±1.5
818.2 ±0.5	7.5± 2.0	2381.5 ±0.8 [c]	3.0±2.1
823.6 ±0.5	7.5± 2.1	2414.2 ±0.4 [c]	11.6±2.3
859.0 ±0.5 [c]	4.3± 0.8	2449.40±0.24	16.0±2.2
875.28±0.18	27 ± 3	2455.6 ±1.3	7.4±2.3
892.1 ±1.0	5.5± 1.5	2470.0 ±1.5 [c]	2.2±1.5
896.1 ±0.3	8.3± 1.6	2484.56±0.22	72 ±8
955.0 ±0.5	13.5± 1.4	2496.2 ±0.4	19 ±3
994.9 ±0.5 [d]	20.3± 2.2	2593.5 ±0.7 [d]	4.0±2.2
1028.5 ±1.0	17 ± 8	2644.6 ±0.5	7 ±3
1060.4 ±1.2	4.9± 1.5	2735.70±0.20	36 ±4
1091.3 ±0.5	5.8± 1.1	2753.09±0.20	14.6±2.3
1102.4 ±0.5	23.0± 2.5	2769.6 ±0.4 [c]	5.8±2.0
1108.80±0.15	164 ± 16	2809.1 ±0.5	8 ±3
1137.0 ±0.4	16 ± 8	2813.6 ±0.5 [c]	6.3±2.1
1155.4 ±0.8 [b,c]	1.6± 1.0	2846.3 ±0.5	4.1±2.2
1177.78±0.12	34 ± 3	2856.1 ±0.3	13 ±4
1195.4 ±0.8	2.8± 2.5	2870.9 ±0.3	19 ±4
1215.85±0.22	16.4± 1.7	2893.9 ±0.4	9 ±8
1267.8 ±0.3	16.0± 1.7	2982.0 ±0.3	27 ±5
1280.9 ±0.3	15.0± 2.1	3004.6 ±0.6	6 ±3
1293.5 ±0.3 [c]	11.2± 2.5	3042.0 ±0.6	6.5±2.1
1304.65±0.22	25 ± 3	3056.6 ±0.6	20±10
1314.1 ±0.3 [b]	15.7± 1.7	3098.7 ±0.5 [c]	7 ±4
1324.9 ±0.3	12.4± 1.2	3113.8 ±0.3	57 ±6
1333.3 ±1.2	1.8± 1.6	3326.6 ±0.4	9.3±2.5
1337.4 ±1.0	1.8± 1.0	3394.7 ±0.6	4 ±3
1351.8 ±1.0	9 ± 3	4293.6 ±0.5	1.1±0.5
1355.8 ±1.0	27 ± 6		
1360.0 ±1.5	4 ± 3		

[a] The error stated for the intensity normalized to 1000 has not been included in the errors of the other intensities.
[b] Doubtful origin.
[c] Not placed in the level scheme.
[d] Placed twice in the level scheme.

3. Conversion-coefficient and x-ray measurements

Figure 2 shows low-energy electron spectra with different enhancements for the ^{91}Kr and the ^{91}Rb decays. The complete conversion-coefficient-measurement results for the first of these decays are collected in Table III. The assigned multipolarities were obtained by comparison with the theoretical values of Hager and Seltzer.[23]

Figure 3 shows differently enhanced spectra recorded with the x-ray detector. Assuming that the total intensity of the ^{91}Rb x rays is produced by the conversion of the 108.65-keV transition, the corresponding α_K value obtained employing the XPG method is 0.070 ± 0.010. This value implies that, in agreement with the result of the conversion-electron measurements, $E1$ is the only possible multipolarity for the transition and that the total intensity of nonobserved and highly-converted transitions is at most ~1% of the 108.65-keV γ-ray intensity.

4. β feedings and Q value

The β feeding to the ground state has been calculated by comparing the γ activities of ^{91}Kr, ^{91}Rb, and ^{91}Sr, under different collection-measuring schedules and using the following arguments: (a) Only Kr isotopes are collected (Ref. 9), an assumption which is supported by the growth curve for the ^{91}Rb activity; (b) the β branches of the ^{91}Sr decay and the ^{91}Y level scheme are well known[24]; (c) the main features of the ^{91}Rb and ^{91}Sr level schemes are correct (see Sec. IV). Thus, for instance, taking into account the necessary correction for the half-lives involved, the saturation values for the total γ-ray intensities feeding directly the ground states of ^{91}Sr and ^{91}Y are calculated. From the ratio of these values and the known total β feeding to the excited levels in ^{91}Y, one obtains the sum of the β feedings to excited states in ^{91}Sr (and, consequently, the feeding to its ground state). In a similar fashion, starting from the Rb-Sr saturated γ-ray intensities ratio one arrives at a value of $20 \pm 2\%$ for the β branch to the

TABLE II. γ-γ coincidence results for ^{91}Kr decay.

Gate transition (keV)	Coincident transitions (keV)
108.65	398.23, 412.15, 613.05, 994.9, 1028.5, 1215.85, 1392.5, 1419.90
501.8	823.6
506.8	630.22, 818.2, 994.9, 1108.80
613.05	108.65, 806.71

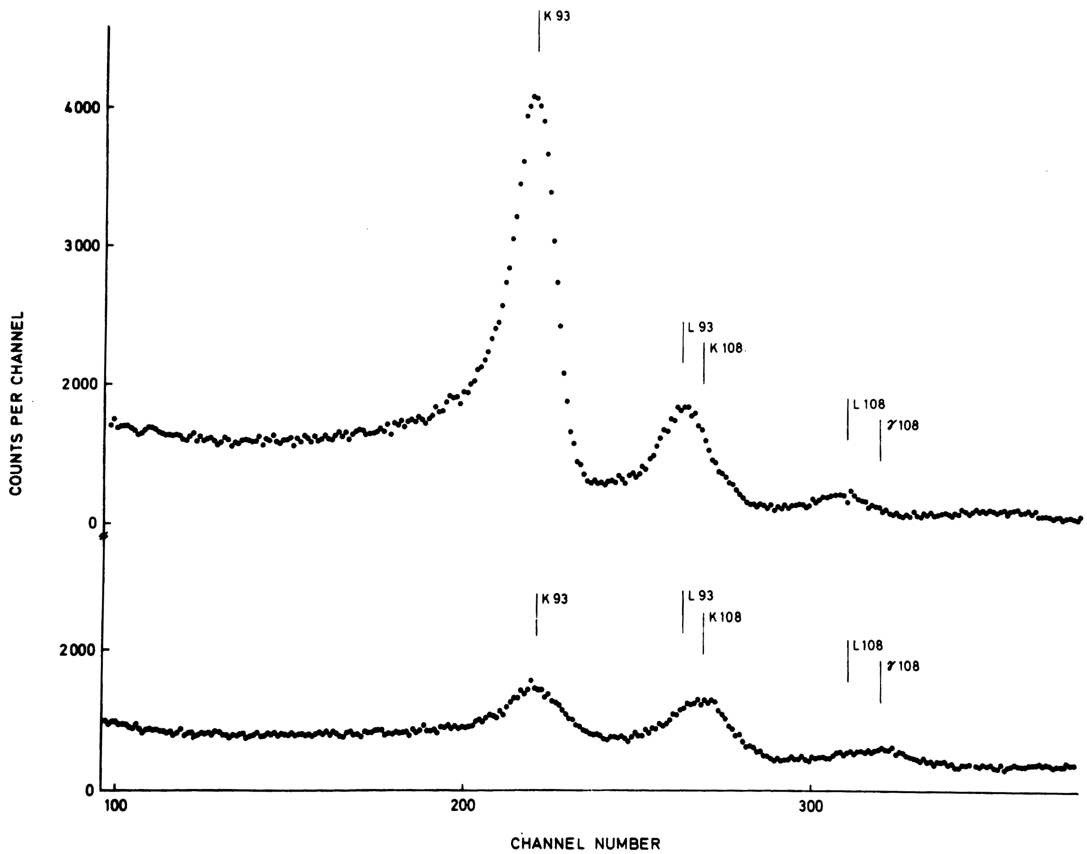

FIG. 2. Partial on-line conversion-electron spectra, recorded with the 3-cm^2 Si(Li) detector. The lower spectrum is the sum of 40 spectra, each accumulated during the first 20 sec of the activity growth. The upper spectrum results from the sum of 50 decays, recorded during 120 sec each, after switching off the separator beam and a waiting period of 30 sec.

^{91}Rb ground state, which compares well with the ~20% deduced from the data of Eidens, Roekl, and Armbruster[4] taking into account the β feedings to all excited levels. For the β feeding to the 108.65-keV level we obtained 23 ± 3%, as against ~10% given by Mason and Johns[5] and ~70% reported by Eidens, Roekl, and Armbruster. The great discrepancy between this latter value and our results is presumably due to the fact that only 2 γ rays were placed by Eidens, Roekl, and Armbruster, as against 94 in our case, and thus they assumed an incorrect distribution of the β feedings.

The energy corresponding to the end point of the singles β-ray spectrum is 5.4 ± 0.3 MeV. Combining this result with the Q values estimated from the (β,γ) coincidence measurements and the proposed level scheme (see Fig. 5), a $Q_\beta = 5.4 \pm 0.2$ MeV was obtained. This value compares well with the 5.7 ± 0.4 MeV reported in Ref. 4 and the 5.08 ± 0.10 MeV given in Ref. 5.

B. ^{91}Rb decay

1. Singles γ spectra; (γ,γ) and (β,γ) coincidences

A typical γ spectrum with enhanced ^{91}Rb activity, taken with a 0.8-mm Pb absorber, is shown in Fig. 4. Our results are summarized in Table IV, showing rather good agreement with the ones of Mason

TABLE III. K-conversion coefficients for ^{91}Kr decay.

Transition energy (keV)	$\alpha_K \times 10^3$	Multipolarity assignment
108.65	67 ± 12	$E1$
398.23	≤8	$E1, E2, M1$
501.8	≤7	$E1, E2, M1, M2$
506.8	3.1 ± 1.0	$E2, M1$
613.05	2.5 ± 1.2	$E2, M1$

and Johns.[5] Some γ rays presented by these authors with no correspondence in our data may be interpreted as single- or double-escape peaks within their energy errors. Our results are also in general agreement with the data of Ref. 21 but our relative intensities are up to about 30% lower.

Table V contains the results of the (γ,γ) coincidence measurements. The (β,γ) coincidences gated by the 2564.30-keV γ ray showed a branch of 3.0 ± 0.3 MeV in coincidence with it.

2. Lifetime determinations

A value of 62 ± 4 sec was found for the ^{91}Rb ground-state decay, in agreement with Ref. 8. The half-life measurement for the 93.40-keV state yielded a value of 90 ± 10 nsec, in good agreement with Refs. 5 and 6. This result, according to the systematics of lower limits for $T_{1/2}$ values[22] implies an $E1$, $M1$, or $E2$ multipolarity for the 93.40-keV transition.

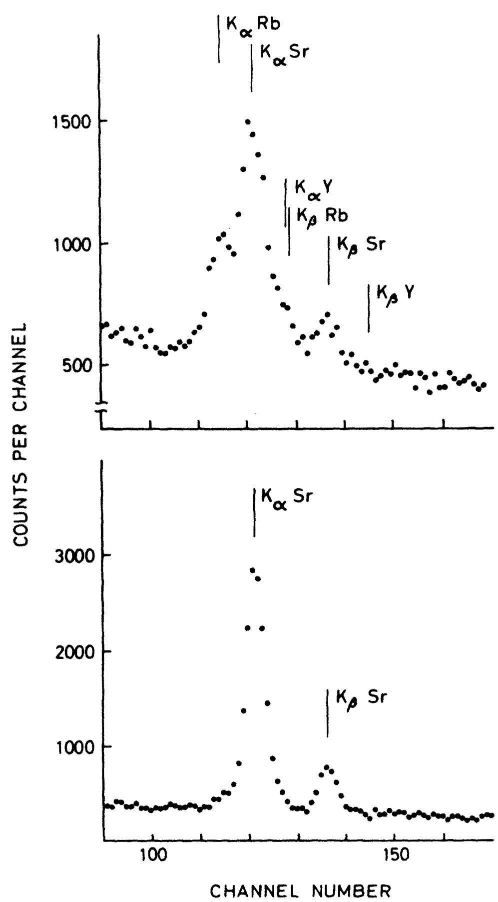

FIG. 3. Partial x-ray spectra as recorded with the 25-mm^2 Si(Li) detector using the moving-tape collector. The upper spectrum is the sum of 30 spectra, each accumulated during the first 60 sec of the activity growth. The lower spectrum results from the corresponding decays, recorded during the following 60 sec after switching off the separator beam.

3. Conversion-coefficient and x-ray measurements

The results of internal-conversion-coefficient measurements for ^{91}Rb-decay transitions are summarized in Table VI. The $E2$ ($\leq 20\%$ $M1$) character obtained for the 93.40-keV transition shown on Fig. 2 coincides with the result given by Malmskog and McDonald[6] from K/L measurements. The upper limit for the percentage of $M1$ admixture has been obtained using not the experimental value for the conversion coefficient itself, but the appropriate end of the corresponding error bar.

If one assumes that the whole intensity of the ^{91}Sr x rays (Fig. 3) originates in the conversion of the 93.40-keV transition, the XPG method yields a value of 1.00 ± 0.12 for its α_K, which corresponds to an $M1$-$E2$ multipolarity. If the stated assumption were wrong, the only other admissible multipolarity would be $E1$, which is however eliminated by the electron-measurement results. Consequently, from the 0.12 error in the above stated α_K value, we limit the total intensity of nonobserved, highly-converted transitions to at most ~10% of the 93.40-keV γ-ray intensity.

4. β feedings and Q value

Using the same procedure as for the ^{91}Kr decay, we obtained a $60\pm10\%$ feeding for the branch to the ^{91}Sr ground state, which improves the lower limit of 30% given in Ref. 7.

The end point of the β distribution was determined to be at 5.7 ± 0.2 MeV. In good agreement with this value, our (β,γ) coincidence result yields $Q_\beta = 5.7\pm0.3$ MeV. Macias-Marques[7] reported a Q value of 5.80 ± 0.09 MeV.

IV. LEVEL SCHEMES

A. Scheme for ^{91}Rb

1. Level energies

The level scheme proposed for ^{91}Rb is shown in Fig. 5. It has been built using the experimental results reported in Sec. III A and contains 94 transitions (96% of the observed γ intensity) within a frame of 31 levels. Logft values have been calculated taking into account the transition intensity balances for each level, the β branch to the ground state, and the Q value. Asterisks indicate γ rays which fit twice in the level scheme. The case of the 994.9-keV ray is special as it is placed twice by coincidences and energy-sum relations.

The levels at 108.65, 501.8, 506.85, 520.80, 721.65, 1103.0, 1137.1, 1324.75, 1501.75, 1528.45, and 1615.0 keV are supported by (γ,γ) coincidence results, energy sums, and intensity relations. The levels at 108.65, 506.85, 721.65, 1501.75, and 1615.0 keV are additionally supported by (β,γ) coincidence results.

The levels at 1304.52, 1666.8, 1875.3, 2055.6, 2449.41, 2456.3, 2496.2, 2593.08, 2753.15, 2809.3, 2844.7, 2981.64, 3041.6, 3056.2, 3113.85, 3325.5, 3377.9, 3394.3, and 4292.5 keV, are built on the only basis of energy sums and intensity relations. All of them are connected to other levels by at least four transitions, except the ones at 2449.41, 2496.2, 2753.15, and 3325.5 keV, which are defined by three transitions, and those at 2809.3, 3056.2, and 4292.5 keV, defined by only two transitions.

2. *Discussion of possible spin-parity assignments*

For odd-N, odd-A nuclei having $N=51-55$, the shell model predicts $J^\pi=\frac{5}{2}^+$. In agreement with this, the reported ground-state assignments for nuclei of this type close to the ^{91}Kr-^{91}Sr region are all $\frac{5}{2}^+$; in particular, for ^{91}Sr this assignment has been well established experimentally.[24] Consequently a ($\frac{5}{2}^+$) assignment for the ^{91}Kr ground state appears to be the most reasonable. On the other hand, since the β decay from the ^{91}Rb ground state to the ^{91}Sr ground state has a $\log ft$ of 6.4, the possibilities[22] for the spin-parity of the ^{91}Rb ground state are $\frac{3}{2}^\pm$, $\frac{5}{2}^\pm$, and $\frac{7}{2}^\pm$. In view of the shell-model predictions, as well as of the odd-Z, odd-A isotopes ground-state systematics in the region, the most probable values are $J^\pi=(\frac{3}{2}^-, \frac{5}{2}^-)$.

The proposed J^π possibilities for the ^{91}Rb ground state, together with the $E1$ character for the 108.65-keV transition and the $\log ft$ value for the β branch to the first excited level of ^{91}Rb, leads to $J^\pi=(\frac{3}{2}^+$ to $\frac{7}{2}^+)$ for this state. The well established parity-changing character of the 108.65-keV transition is of especial importance and is discussed further from the theoretical point of view in Sec. V.

The conversion coefficient for the 506.8-keV ground-state transition implies the same parity for the 506.85-keV level as for the ground state; thus the multipolarity assignment for the 398.23-keV transition deexciting this level is restricted to the $E1$ possibility (see Table III). Taking into account the $\log ft=6.3$ for the β branch from the ^{91}Kr ground state, the possible J^π values for the 506.85-keV level are ($\frac{3}{2}^-$ to $\frac{7}{2}^-$).

In view of the $E2,M1$ character of the 613.05-keV transition, the parity of the 721.65-keV level is positive; possible spin values for this level are again ($\frac{3}{2}$ to $\frac{7}{2}$).

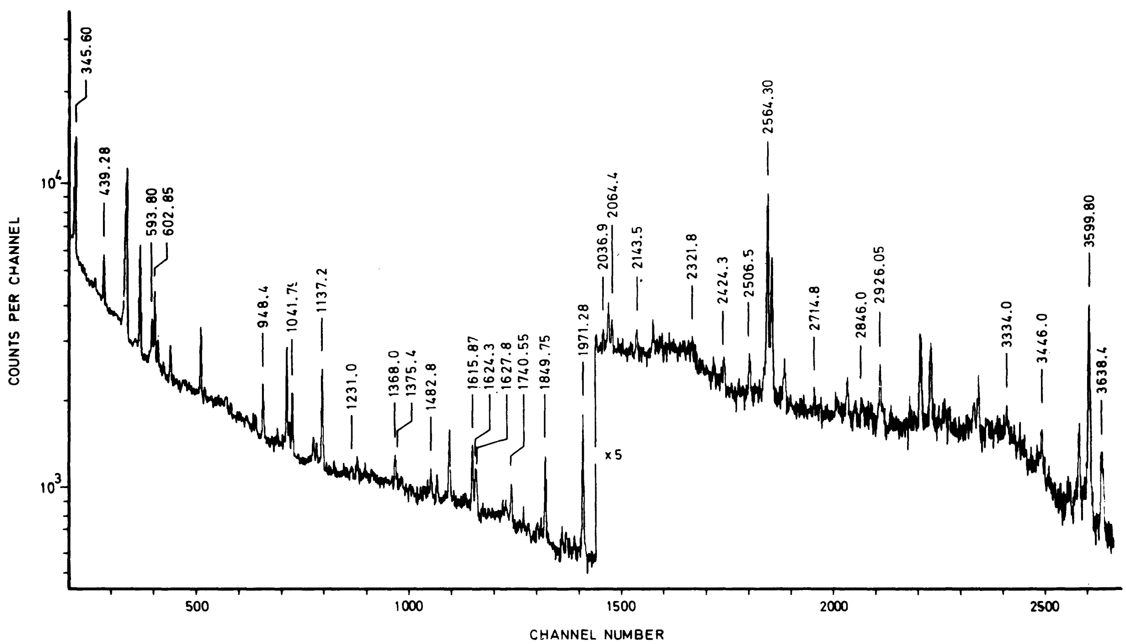

FIG. 4. Partial γ spectra with enhanced Rb activity taken by interposing a 0.8-mm-thick Pb absorber. Some of the Rb decay full-energy peaks are labeled with the corresponding energy value.

TABLE IV. γ rays observed in the decay of ^{91}Rb.

Present work Energy (keV)	Present work Relative intensity [a]	Mason and Johns (Ref. 5) Energy (keV)	Mason and Johns (Ref. 5) Relative intensity
93.40 ± 0.10	1000 ± 100	93.1 ± 0.3	1000
345.60 ± 0.12	340 ± 30	346.0 ± 0.5	316
376.3 ± 0.5	6.2 ± 2.1		
381.7 ± 1.2 [b]	4.1 ± 2.2		
389.3 ± 0.5 [b]	8 ± 4		
439.28 ± 0.10	77 ± 10	439.3 ± 0.5	71
593.80 ± 0.20	52 ± 12	593.1 ± 0.2	45
602.85 ± 0.13	102 ± 12	602.7 ± 0.2	105
736.6 ± 0.5 [b]	4.3 ± 2.1		
948.4 ± 0.3	61 ± 13	947.8 ± 0.3	74
1041.79 ± 0.15	83 ± 7	1041.3 ± 0.3	89
1137.2 ± 0.5	148 ± 15	1137.4 ± 0.2	124
1231.0 ± 2.0	5 ± 4		
		1301 ± 2	21
1368.0 ± 0.5	41 ± 4		
1375.4 ± 0.5	12 ± 4		
		1436 ± 1	21
1482.8 ± 0.5	21.3 ± 2.3	1483.2 ± 0.8	42
1615.87 ± 0.19	98 ± 12	1616.0 ± 0.5	89
1624.3 ± 0.5	60 ± 6	1625.0 ± 0.7	42
1627.8 ± 0.5	40 ± 4	1629.1 ± 0.8	32
1740.55 ± 0.23 [b,c]	67 ± 15		
1767.6 ± 0.5 [b]	11 ± 5		
1796.5 ± 0.5	18 ± 3		
1849.75 ± 0.12	147 ± 15	1849.5 ± 0.2	100
		1905 ± 2	34
		1914 ± 1	31
1919.7 ± 1.3 [b]	15 ± 3		
1942.8 ± 0.5	19 ± 4		
1971.28 ± 0.12	310 ± 30	1971.2 ± 0.3	258
		1982 ± 2	21
2014.3 ± 0.5	10 ± 5		
2036.9 ± 0.5 [b]	17 ± 7	2036 ± 2	21
2064.4 ± 0.3	33 ± 4		
2143.5 ± 0.5	27 ± 7		
2321.8 ± 0.6	22 ± 4	2322 ± 1	26
2331.2 ± 1.3	7 ± 4		
2424.3 ± 0.5 [c]	22 ± 4		
2506.5 ± 0.5	55 ± 6	2505 ± 1	58
2564.30 ± 0.15	570 ± 60	2564.3 ± 0.2	526
2714.8 ± 0.3 [b]	21 ± 4	2712 ± 1	26
		2722 ± 2	21
2846.0 ± 0.5	19 ± 10		
2919.7 ± 1.6 [c]	9 ± 4		
2926.05 ± 0.25 [b,c]	65 ± 7	2925.7 ± 0.6	95
3035.0 ± 1.0 [d]	7 ± 6		
3334.0 ± 0.5	21 ± 6		
3446.0 ± 0.5 [b]	22 ± 6	3446 ± 1	63
3599.80 ± 0.15	360 ± 40	3600.0 ± 0.3	368
3638.4 ± 0.5	45 ± 10	3640 ± 1	92
		3738 ± 2	31
		3752 ± 2	~26
3840.2 ± 1.0 [b]	31 ± 8	3842 ± 1	55
3845.0 ± 0.8 [b]	43 ± 8		
3985.2 ± 1.8 [b]	6 ± 4		
4044.1 ± 0.5 [b]	19 ± 6		
4078.5 ± 0.5	160 ± 20	4078.5 ± 0.5	150
4158.8 ± 1.2 [b]	8 ± 3		
4169.8 ± 1.3 [c]	8 ± 7		
4251.0 ± 0.6 [b]	18 ± 9	4252 ± 1	26
4265.2 ± 0.3	51 ± 6	4265 ± 1	53
4452.5 ± 1.2	11 ± 5		
		4497 ± 3	13
4747.0 ± 2.3 [b]	4 ± 3		
4801.7 ± 1.8	4 ± 3		

[a] The error stated for the 93.40-keV transition intensity has not been taken into account in calculating the error for the other intensities.

[b] Not placed in the level scheme.

[c] Doubtful origin.

[d] Used twice in the level scheme.

In view of the allowed character of their β feedings, the most probable assignments for the spin-parity for the levels at 1615.0, 2593.09, 2844.7, 2981.64, 3041.6, 3056.2, 3113.85, 3325.5, 3377.9, 3394.3, and 4292.5 keV are also ($\frac{3}{2}^+$ to $\frac{7}{2}^+$).

TABLE V. γ-γ coincidence results for ^{91}Rb decay.

Gate transition (keV)	Coincident transitions (keV)
93.40	345.60, 602.85, 948.4, 1137.2, 1624.3, 1849.75, 1971.28, 2331.2, 2506.5, 2564.30, 3334.0, 3599.80
345.60	93.40, 602.85, 1624.3, 3638.4
602.85	93.40, 345.60, 1615.87

It should be remarked that the log ft values used in the foregoing discussion are not affected by the uncertainties in either the intensity balances or the Q_β value.

TABLE VI. K-conversion coefficients for ^{91}Rb decay.

Transition energy (keV)	$\alpha_K \times 10^3$	Multipolarity assignment
93.40	1050 ± 100	$E2$ (≤20% $M1$)
345.60	9 ± 4	$E2,M1$
602.85	1.8 ± 1.1	$E2,M1$
948.4	0.6 ± 0.3	$E2,M1$
1041.79	0.52 ± 0.22	$E2,M1$
1137.2	0.36 ± 0.15	$E2,M1$

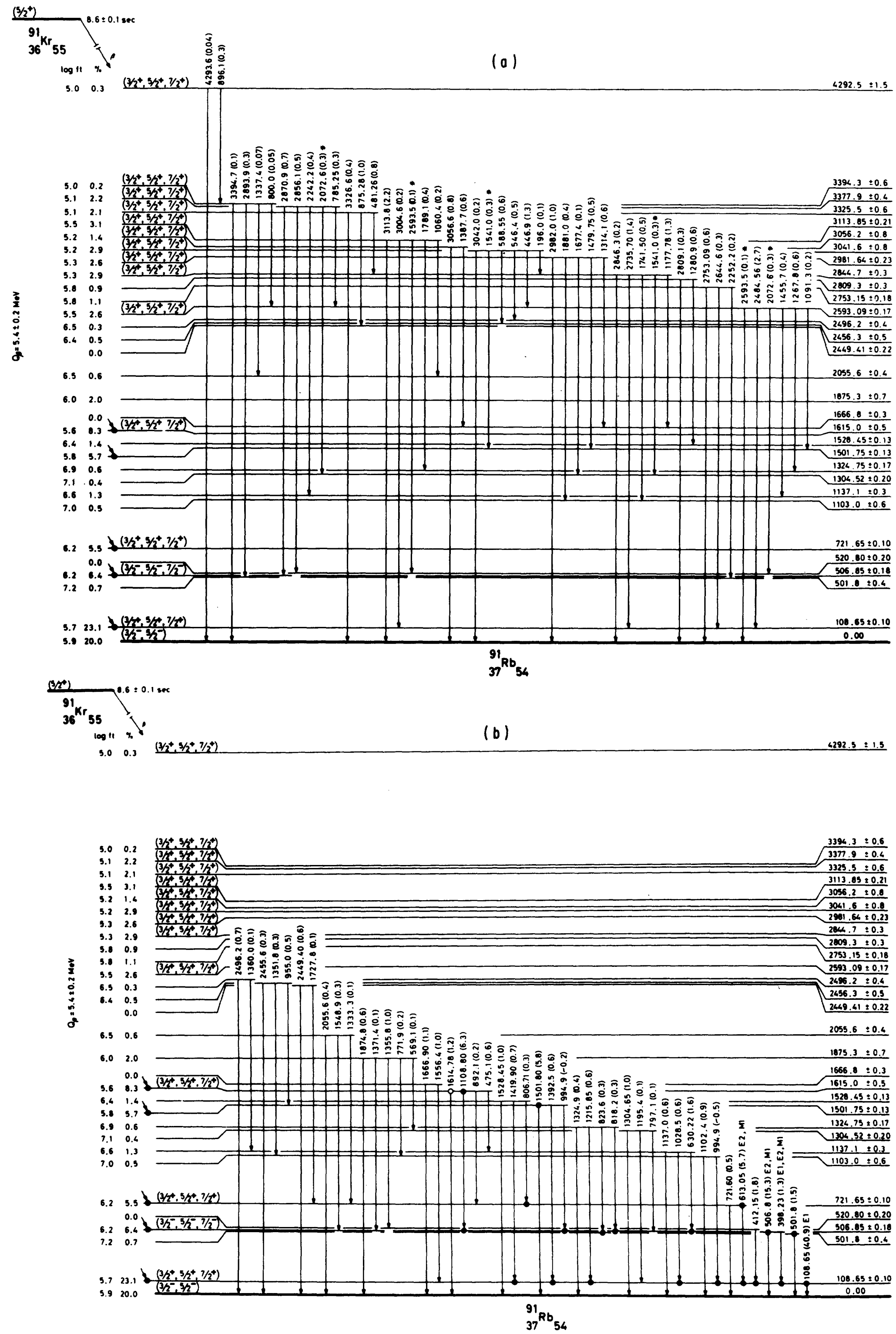

FIG. 5. Level scheme for ^{91}Rb. Above each transition are given its energy and intensity per 100 disintegrations. Adopted multipolarities are indicated. Well established coincidence relations are marked by full dots; questionable ones by open circles. Three doubly placed γ rays are marked with asterisks; for the two 994.9-keV transitions see Sec. IV A 1.

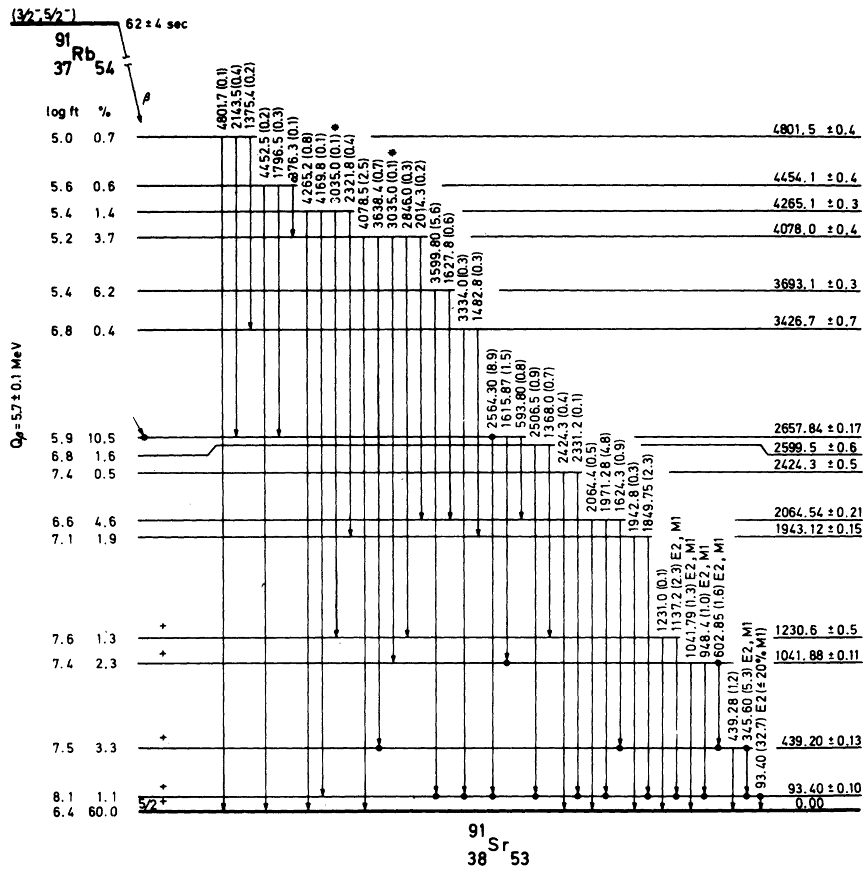

FIG. 6. Level scheme for ^{91}Sr. Above each transition is given its energy and intensity per 100 disintegrations. Adopted multipolarities are indicated. Coincidence relations are marked by dots; a doubly placed γ ray with asterisks.

B. Scheme for ^{91}Sr

1. Level energies

The proposed level scheme, built on the experimental results reported in Sec. III B, is shown in Fig. 6. It contains 39 transitions (92% of the observed γ intensity) and only one ray has been placed twice. Above 2 MeV this scheme differs significantly from the one given in Ref. 4. As for the ^{91}Kr decay, $\log ft$ values have been calculated taking into account the transition-intensity balance for each level, the β branch to the ground state, and the Q value, the results not being affected either by the errors in the balances or by the error in Q_β.

The levels at 93.40, 439.20, 1041.88, 1230.6, 1943.12, 2064.54, 2424.3, 2599.5, 2657.84, 3426.7, 3693.1, and 4078.0 keV are based on coincidence results, energy sums, and intensity relations.

The levels at 4265.1, 4454.1, and 4801.5 keV are supported only by energy sums and intensity relations. The first of these is connected to other levels by four transitions, and the other ones, by only three.

2. Discussion of possible spin-parity assignments

The $\frac{5}{2}^+$ spin-parity assignment for the ^{91}Sr ground state is well supported experimentally.[24] Thus the $E2$ ($\leq 20\%$ $M1$) multipolarity determined for the 93.40-keV γ ray, leads to $(\frac{1}{2}$ to $\frac{9}{2})^+$ as possible J^π values for the first excited level in ^{91}Sr.

For the levels at 439.20, 1041.88, and 1230.6 keV we propose a positive-parity assignment in view of our determination of the $E2,M1$ character for the transitions deexciting them to states of positive parity. Spin possibilities for these levels are $(\frac{1}{2}$ to $\frac{9}{2})$.

The levels at 3693.1, 4078.0, 4265.1, 4454.1, and 4801.5 keV probably have negative parity in view of the allowed β feeding from the ^{91}Rb ground state deduced from the corresponding $\log ft$ values.

V. DISCUSSION

The ^{91}Rb level scheme established in this work shows as an experimentally well established fact the existence of low-lying excited states with parity opposite to that of the ground state. The most probable assignments are $\pi = -1$ for the ground state and $\pi = +1$ for the first excited state. This cannot be explained on the basis of the spherical shell model, since in that picture the odd proton should occupy the $f_{5/2}$ shell and low-energy excitations would also lead to negative-parity levels. The first possibility for positive-parity states involves the $g_{9/2}$ shell which is much too high in energy when compared with the experimental values. We are thus led to assume a stable deformation for at least some of the excited levels. The value $J^\pi = \frac{9}{2}^+$ for the first excited level is very improbable in view of our experimental results and consequently[25] the possibility of negative deformations is ruled out. We are thus left with the $[440]\frac{1}{2}^+$ and $[431]\frac{3}{2}^+$ Nilsson orbitals as possible sources for the positive-parity band, in the region of deformations with $\epsilon \sim 0.1-0.15$.

Within the picture of a deformed nucleus, the 506.85-keV level might then be considered as the first excited member of a rotational band built on top of the ground state. This assumption appears to be strengthened by the fact that this state decays by a rather strong $E2, M1$ transition. The small value of $\hbar/2J$ corresponds to a transitional pattern which is consistent with the hypothesis that the nucleus is close to the border of a deformed region.[1]

For the case of ^{91}Sr the structure of the first excited state has been discussed[6] in terms of Talmi calculations.[26] The present experimental results do not provide further support for this interpretation nor do they show disagreement with it; the possibility of collective excitations cannot be ruled out and they would help to understand the rather high $B(E2)$ value (~14 single-particle units) for the 93.40-keV transition.

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