# Two-Hole and Two-Particle-Four-Hole States in $^{88}$Sr and the Decay of 17.8-min $^{88}$Rb†

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The population of levels of $^{88}$Sr from the decay of 17.8-min $^{88}$Rb has been investigated by studying the $^{88}$Rb $\gamma$ rays with a Ge(Li) Compton-suppression spectrometer and with large-volume Ge(Li) detectors. 42 $\gamma$ rays are identified as originating from $^{88}$Rb, and 31 of them are assigned to 18 levels of $^{88}$Sr. Discrepancies which existed among previous Ge(Li) $\gamma$-ray studies are resolved. The levels populated from $^{88}$Rb decay are compared with the levels of $^{88}$Sr populated by other reactions. The nature of the levels is discussed in terms of two-hole and two-particle–four-hole excitations and collective modes of excitations.

## I. INTRODUCTION

As an $N = 50$ nucleus whose excited states can be produced by a variety of reactions, $^{88}$Sr has recently been the object of a considerable number of decay scheme studies.[1-7] In an attempt to resolve some of the inconsistencies among the decay-scheme results, we have reinvestigated the decay of $^{88}$Rb with a Ge(Li) Compton-suppression spectrometer and with large-volume Ge(Li) detectors. Our measurements have revealed seven levels previously unobserved in $\beta$ decay. In conjunction with data from recent nuclear-reaction experiments,[8] we have been able to clarify spin-parity assignments and provide configuration information for comparison with recent microscopic neutron one-particle–one-hole (1p-1h) and proton one-particle–three-hole (1p-3h) calculations.[9-11]

## II. EXPERIMENTAL PROCEDURE

Separate and independent experiments were carried out at Lawrence Livermore Laboratory (LLL) and at the Nuclear Radiation Center at Washington State University (WSU). At LLL, sources of $^{88}$Rb were prepared by short irradiations of RbCl enriched to 99% in $^{87}$Rb in the thermal-neutron flux of the Livermore pool-type reactor (LPTR) followed by elution from a thallium phosphotungstate column. Sources of $^{88}$Kr were prepared from gross fission products by gas chromatography; the $^{88}$Rb daughter was allowed to grow in and the $^{88}$Kr was boiled off before counting.[12] At WSU, sources of $^{88}$Rb were prepared from short irradiations of natural $Rb_2SO_4$ in the WSU TRIGA III reactor.

Direct $\gamma$-ray spectra were taken at LLL using several Ge(Li) detectors, all with cooled field-effect-transistor preamplifiers. High-energy $\gamma$-ray spectra were taken with a 40-cm$^3$ Ge(Li) detector. For studying lower-energy $\gamma$ rays a 7-cm$^3$ Ge(Li) detector was used in the Compton-suppression system.[13] At WSU a 60-cm$^3$ Ge(Li) detector was used to investigate the $^{88}$Rb high-energy $\gamma$-ray spectrum.

## III. RESULTS

Figure 1 shows the $\gamma$-ray spectrum of $^{88}$Rb together with $^{88}$Kr taken with the LLL Compton-suppression spectrometer. Figure 2 shows the $\gamma$-ray spectrum of the high-energy region taken with an LLL 40-cm$^3$ Ge(Li) detector. By comparison of the $\gamma$-ray spectra of $^{88}$Rb alone (free from $^{88}$Kr) with those from $^{88}$Rb together with $^{88}$Kr, spurious $\gamma$ rays were eliminated. The energy calibration of the intense $\gamma$ rays was done by simultaneously observing the $^{88}$Rb source with known standard $\gamma$ rays.[14] These energy values were then used as internal standards to obtain the values of the weaker peaks using the Gunnink-Niday code[14] on the Livermore CDC computers. The reported $\gamma$-ray intensities were calculated with efficiency calibrations made using International Atomic Energy Agency standards and $^{56}$Co and $^{66}$Ga sources. Table I lists the energies and intensities of all the observed $\gamma$ rays which were assigned to the decay of $^{88}$Rb. There are several $\gamma$ rays included in the list whose low intensity precluded placement in the decay scheme. We have placed 31 of 42 $\gamma$ rays. With the Compton-suppression system we were able to observe $\gamma$ rays of energies less than 898 keV; these $\gamma$ rays had been previously unobserved because they were masked by Compton events from higher-energy $\gamma$ rays.

## IV. DECAY SCHEME

The decay scheme of $^{88}$Rb shown in Fig. 3 is based on our $\gamma$-ray measurements of the energies and intensities of the $^{88}$Rb $\gamma$ rays. The $\beta$ branchings were calculated on the basis of a ground-state $\beta$-group intensity of 76.2% as measured by Ragaini and Knight.[1] The $\log_{10}ft$ values were computed using a $Q_\beta$ value of $5.199 \pm 0.004$ MeV calculated by Ragaini and Knight[1] from other experimenters' data for the $^{88}$Sr neutron binding energy, the $^{87}$Rb $Q_\beta$ value, and the $^{87}$Rb neutron binding energy. The placement of the $\gamma$ rays and the spin-parity assignments were made on the basis of internal-energy agreements, other $\gamma$-$\gamma$ coincidence measurements,[1] and comparisons with reaction experiments on $^{88}$Sr levels. Five of the 24 previously unobserved $\gamma$ rays were placed between levels which had already been established; these $\gamma$ rays have energies of 417, 432, 439, 1257, and 1680 keV. The nine $\gamma$ rays at 1218, 2199, 2388, 2797, 3525, 3611, 3966, 4037, and 4634 keV involve levels postulated in this study. The levels at 4634, 4037, 3966, 3611, and 3525 keV were placed because the observed $\gamma$ rays of those energies are too energetic to be other than ground-state transitions. The levels at 4224 and 3952 keV were postulated to decay to the 1836- and 2734-keV levels by the 2388- and 1218-keV $\gamma$ rays, respectively, because of the agreement of the level energies with reaction data. Table II summarizes the $\beta$-decay data calculated from our $\gamma$-ray measurements. The energy values for the $^{88}$Sr levels were calculated from weighted averages of the

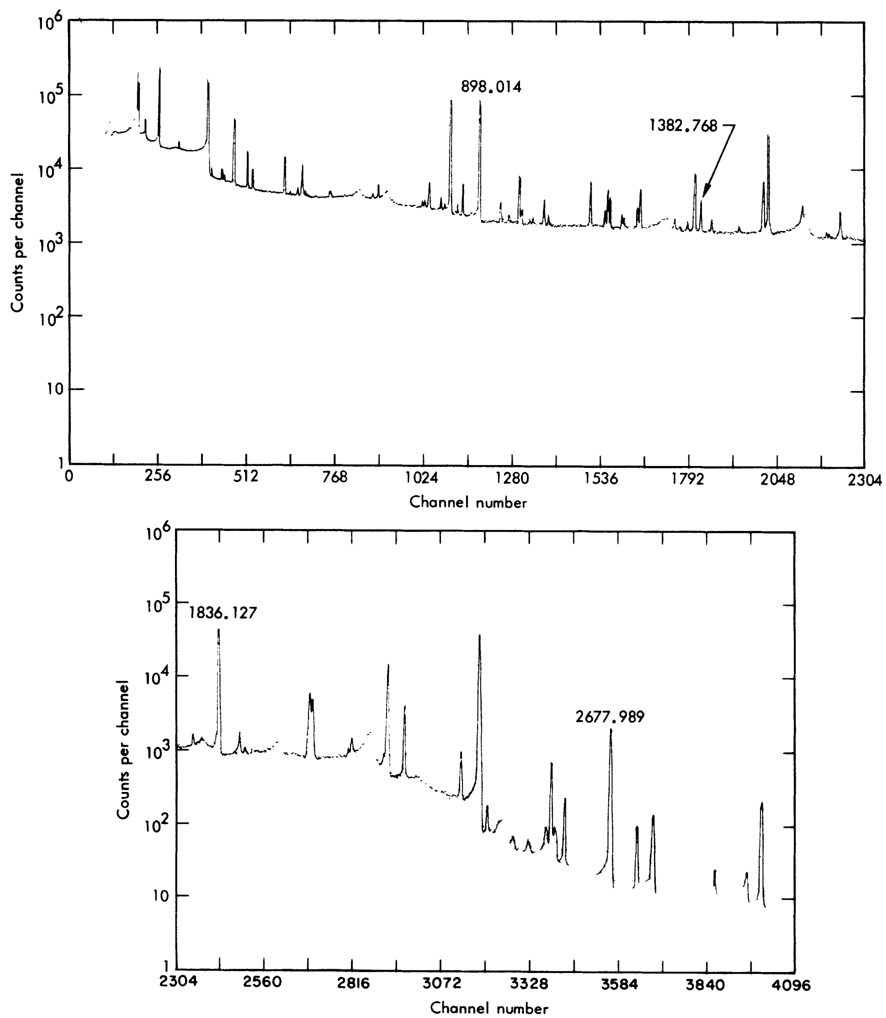


FIG. 1. $\gamma$-ray spectrum of a source of $^{88}$Rb and $^{88}$Kr taken with the LLL Compton-suppression Ge(Li) spectrometer.

appropriate $\gamma$-ray energies corrected for nuclear recoil.

We have tentatively included the level at 3150 keV in Table II because of the possible assignment of the 1313.9-keV $\gamma$ ray as deexciting the $0^+$ 3150-keV level and feeding the $2^+$ level at 1836 keV. The only other experimental results on this level are from the $(t, p)$ reaction[15] which populates a $0^+$ level at $3150 \pm 3$ keV. Because the level energy calculated from the $\gamma$-ray energies agrees well with the $(t, p)$ data and because the $\log_{10}ft$ value of >9.7 is not inconsistent with a $2^- \rightarrow 0^+$ $\beta$ transition, we include this level in parentheses. But since there is no direct evidence to support this assignment, we do not include the data in the decay scheme.

### A. Comparison with Previous Decay-Scheme Studies

Table III contains a comparison of our results with the previous decay studies of $^{88}$Rb. A level at 2574 keV was postulated by Aras *et al.*[5] to decay to the ground state by a 2574-keV $\gamma$ ray. The other investigators have assigned this $\gamma$ ray as connecting the levels at 4514 and 1836 keV. A level at 3598 was postulated by Luukko and Holmberg[4] to decay to the ground state, but no other experiment has corroborated the existence of the corresponding $\gamma$ ray. The level at 4227 keV was placed by Aras *et al.*[5] on the basis of an observed coincidence between a 2390-keV $\gamma$ ray and the 1836-keV $\gamma$ ray. We observe this $\gamma$ ray at $2388.00 \pm 0.75$ keV and concur in its assignment, as no experimental or theoretical evidence has ever favored a 2388-keV level and the $Q_\beta$ energetics forbid any higher placement. The level at 4269 keV was reported by Lycklama, Araner, and Kennett[2] to decay to the 2734-keV level by a 1535-keV $\gamma$ ray; such a $\gamma$ ray has not been observed in the other published experiments.

Because of energy-resolution limitations of their Ge(Li) detector, Hess and co-workers[3] could not distinguish the deexcitation $\gamma$ rays of the 4846- and 4854-keV levels and consequently postulated a level at 4850 keV. It appears that similar problems caused Luukko and Holmberg[4] and Aras *et al.*[5] to postulate levels at 4852 and 4850 keV, respectively, but not the level at 4846 keV. In each of these three works, the 3009.8-keV $\gamma$ ray was assigned as connecting the 1836.1- and 4853.7-keV levels, whereas we have assigned the $\gamma$ ray between the 4846.0- and 1836.1-keV levels.

The spin-parity assignments among the decay-scheme experiments are generally consistent. The most significant disagreement occurs for the 4744-keV level. It is $\beta$ fed with $\log_{10}ft = 5.9$, and it apparently decays only to the ground state with any observable intensity. These data indicate a $1^\pm, 2^+$ assignment for the level. Other $2^+$ assign-

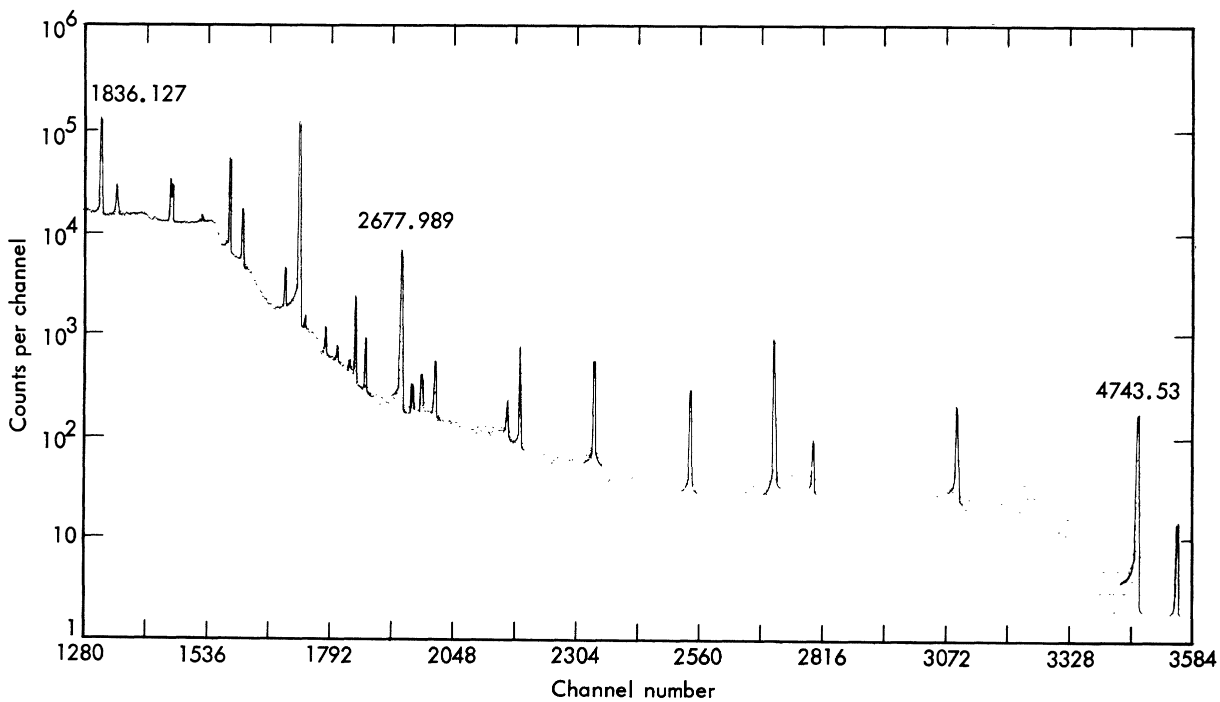


FIG. 2. $\gamma$-ray spectrum of the high-energy region for $^{88}$Rb decay taken with an LLL 40-cm$^3$ Ge(Li) detector.

TABLE I. Energies, positions, and intensities of $\gamma$ rays emitted in the decay of 17.8-min $^{88}$Rb.

| Energy ($\Delta E$) (keV) | Relative intensity ($\Delta I$) | From level (keV) | To level (keV) |
|---|---|---|---|
| 417.00 (20) [a] | 0.17 (6) | 3635 | 3218 |
| 431.90 (20) [a] | 0.37 (12) | 4846 | 4514 |
| 439.19 ( ) [a] | 0.64 (17) | 4854 | 4414 |
| 484.75 (15) | 1.15 (29) | 3218 | 2734 |
| 625.27 (15) [a] | 0.61 (15) | ... | ... |
| 890.68 (40) [b] | 7 (4) | ... | ... |
| 898.014 (19) [c] | 506 (5) | 2734 | 1836 |
| 916.90 (80) [a] | 0.50 (20) | ... | ... |
| 1027.30 (30) | 0.51 (21) | 4514 | 3486 |
| 1217.67 (15) | 2.38 (31) | 3952 | 2734 |
| 1239.50 (50) [a] | 0.2 (1) | (4458) | (3218) |
| 1257.20 (50) [a] | 0.60 (20) | 4744 | 3486 |
| 1297.00 (50) [a] | 0.40 (30) | (4031) | (2734) |
| 1313.90 (50) [a] | ≤0.3 | (3150) | (1836) |
| 1382.768 (22) | 32.54 (57) | 3218 | 1836 |
| 1555.7 (8) [a] | 1.0 (8) | ... | ... |
| 1635.0 (8) [a] | ≤0.3 | ... | ... |
| 1668.8 (8) [a] | 1.1 (5) | ... | ... |
| 1679.90 (30) [a] | 2.16 (45) | 4414 | 2734 |
| 1779.715 (95) | 10.00 (50) | 4514 | 2734 |
| 1799.52 (15) | 1.84 (39) | 3635 | 1836 |
| 1836.127 (25) | 1000.0 (3) | 1836 | g.s. |
| 2111.792 (90) | 6.06 (51) | 4846 | 2734 |
| 2119.839 (50) | 21.92 (98) | 4854 | 2734 |
| 2195.60 (50) [a] | 1.20 (50) | (4031) | (1836) |
| 2199 ( ) [a] | <0.1 | 4037 | 1836 |
| 2388.00 (75) [a] | 1.27 (39) | 4224 | 1836 |
| 2577.896 (81) | 10.77 (63) | 4414 | 1836 |
| 2621.9 (9) [a] | 0.53 (15) | (4458) | (1836) |
| 2677.989 (58) | 112.1 (12) | 4514 | 1836 |
| 2734.170 (50) | 4.49 (35) | 2734 | g.s. |
| 2797.4 (5) [a] | 0.07 (4) | 4633 | 1836 |
| 3009.815 (80) | 16.7 (4) | 4846 | 1836 |
| 3017.6 (2) | 0.2 (1) | 4854 | 1836 |
| 3218.75 (11) | 15.5 (8) | 3218 | g.s. |
| 3486.76 (12) | 7.8 (2) | 3486 | g.s. |
| 3525 (1) [a] | 0.3 (1) | 3525 | g.s. |
| 3611.5 (10) [a] | 0.15 (7) | 3611 | g.s. |
| 3966.20 (80) [a] | 0.3 (1) | 2966 | g.s. |
| 4037.20 (60) [a] | 0.5 (1) | 4037 | g.s. |
| 4633.50 (10) [a] | 0.12 (4) | 4633 | g.s. |
| 4743.53 (5) | 4.90 (10) | 4744 | g.s. |
| 4853.87 (27) | 0.36 (6) | 4854 | g.s. |

[a] Previously unobserved $\gamma$ rays.
[b] Assignment to $^{88}$Rb decay is questionable.
[c] $\gamma$-ray energy taken from R. Greenwood, Idaho Nuclear Corporation, private communication.

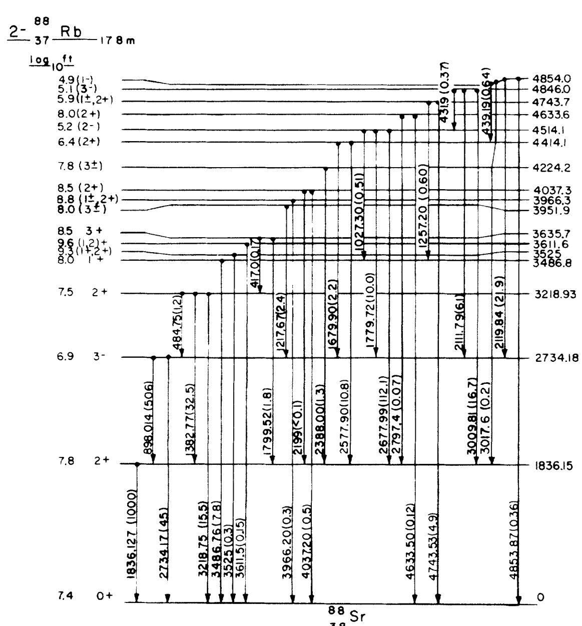


FIG. 3. Decay scheme of $^{88}$Rb. Energies are given in keV. Level separations are not necessarily drawn to scale. The $Q_\beta$ is taken to be 5.199 MeV as calculated by Ragaini and Knight (Ref. 1).

ments[1, 2] are based on the assumption that this level is the same as the 4748-keV level populated in the $(d, p)$ reaction.[16]

We assign a $1^-$ value for the 4854-keV level from the low $\log_{10}ft$ value and the decay to the ground state. A $2^-$ value would mean that the $\gamma$-ray decay ratio was $M1/M2 = 61$, whereas Moskowski's estimates are $M1/M2 = 3.2\times 10^4$. We could not explain such a fast $M2$ transition under those circumstances. Kawase[6] has assigned a spin value of $2^-$ to the 4854-keV level on the basis of a 2-1-0 cascade suggested by observed angular correlations for a 1366-3489-keV $\gamma$-ray pair. However, we do not observe a $\gamma$ ray at 1366 keV, and yet we observe $\gamma$ rays in that energy region with intensities less than $\frac{1}{10}$ the reported intensity of the 1366-keV $\gamma$ ray. We suggest that the reported 1366-keV $\gamma$ ray is either the double-escape peak of the $\gamma$ ray at 2388 keV or a contaminant.

### B. Comparison with Other Reactions

Table IV compares the results of our study with other modes of population of $^{88}$Sr levels,[15–20] and the agreements are quite good. The excited states at 1836, 2734, 3219, 3487, and 3636 keV are well known and need no further discussion.

TABLE II. $\beta$ decay of 17.8-min $^{88}Rb$.

| Energy level (keV) | (%) $\beta$ | $\log_{10} ft$ | $J^\pi$ |
|---|---|---|---|
| 0 | 76.2 | 7.4 | $0^+$ |
| 1836.15 ± 0.03 | 7.3 | 7.8 | $2^+$ |
| 2734.18 ± 0.05 | 10.8 | 6.9 | $3^-$ |
| (3150.1) [a] | ≤0.007 | ≥9.7 | $0^+$ |
| 3218.93 ± 0.05 | 1.1 | 7.5 | $2^+$ |
| 3486.8 ± 0.1 | 0.15 | 8.0 | $1^+$ |
| 3525 ± 1 | 0.007 | 9.3 | $(1^+, 2^+)$ |
| 3611.6 ± 1 | 0.003 | 9.6 | $(1, 2)^+$ |
| 3635.7 ± 0.1 | 0.047 | 8.5 | $3^+$ |
| 3951.9 ± 0.2 | 0.055 | 8.0 | $(3^\pm)$ |
| 3966.3 ± 0.8 | 0.007 | 8.8 | $(1^\pm, 2^+)$ |
| 4037.3 ± 0.6 | 0.011 | 8.5 | $(2^+)$ |
| 4224.2 ± 0.8 | 0.029 | 7.8 | $(3^\pm)$ |
| 4414.1 ± 0.1 | 0.28 | 6.4 | $(2^+)$ |
| 4514.1 ± 0.1 | 2.8 | 5.2 | $(2^-)$ |
| 4633.6 ± 0.1 | 0.004 | 8.0 | $(2^+)$ |
| 4743.7 ± 0.1 | 0.13 | 5.9 | $(1^\pm, 2^+)$ |
| 4846.0 ± 0.1 | 0.53 | 5.1 | $(3^-)$ |
| 4854.0 ± 0.1 | 0.52 | 4.9 | $(1^-)$ |

[a] This assignment based on indirect evidence.

Because of its extremely low intensity, we cannot report the $\gamma$ ray at 3525 keV more accurately than ±1 keV. As this $\gamma$ ray is too energetic not to be a ground-state transition, we assign a level at 3525 keV and we conclude that it is the same as the one reported at 3522.6 keV in the $(n,\gamma)$ reaction.[17] Our $\beta$ and $\gamma$ data are consistent with the $2^+$ assignment by Lycklama and Kennett[17] although we cannot eliminate a possible $1^+$ assignment.

We have tentatively identified the 3612-keV level populated by $\beta$ decay with the level at 3606 keV populated by the $(^3He, d)$ reaction[18] and the level at 3607 keV populated by the $(p, p')$ reaction.[19] The $\beta$-decay $\log_{10} ft$ value (9.6) and the $\gamma$ decay (100% to the ground state) of the 3612-keV level are consistent with a $2^+$ assignment, but a possible $1^+$ assignment cannot be ruled out on the basis of the decay data.

There is little doubt that the $(n,\gamma)$ reaction[17] and the $^{88}Rb$ $\beta$ decay are populating the same level at 3952 keV. In the $(n,\gamma)$ reaction the 3952-keV level is populated by a direct $\gamma$ transition from the capture state, and in the $\beta$ decay the $\log_{10} ft$ value of 8.0 implies an allowed, first-forbidden, or first-forbidden unique $\beta$ transition. Since the $(n,\gamma)$ reaction data permit spin-parity values of $3^\pm$, $4^\pm$, $5^\pm$, and $6^\pm$, and since the $\beta$-decay data allow assignments of $0^+$, $1^\pm$, $2^\pm$, and $3^\pm$, then the spin-parity value which is consistent with both experiments is $3^\pm$. However, the $(^3He, d)$ reaction[18] populates a level at 3955 keV with an $l_p$ value of 4, permitting spin-parity values of $2^-$ to $6^-$. If the levels in question are the same, then a spin-parity assignment of $3^-$ is the only one consistent with all the experimental data.

The level at 3966 keV has not been observed in

TABLE III. Comparison of levels of $^{88}Sr$ populated by $^{88}Rb$ decay from different experiments.

| This work | | Ref. 1 | | Ref. 2 | | Ref. 3 | | Ref. 4 | | Ref. 5 | | Ref. 6 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $E$ (keV) | $J^\pi$ | $E$ (keV) | $J^\pi$ | $E$ (keV) | $J^\pi$ | $E$ (keV) | $J^\pi$ | $E$ (keV) | $J^\pi$ | $E$ (keV) | $J^\pi$ | $E$ (keV) | $J^\pi$ |
| 0 | $0^+$ | 0 | $0^+$ | 0 | $0^+$ | 0 | $0^+$ | 0 | $0^+$ | 0 | $0^+$ | 0 | $0^+$ |
| 1836.15 | $2^+$ | 1836.1 | $2^+$ | 1836.1 | $2^+$ | 1837 | $2^+$ | 1836 | $2^+$ | 1837 | $2^+$ | 1836 | $2^+$ |
| ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | 2574 | ... | ... | ... |
| 2734.18 | $3^-$ | 2734.1 | $3^-$ | 2734.1 | $3^-$ | 2735 | $3^-$ | 2735 | $3^-$ | 2736 | $3^-$ | 2734 | $3^-$ |
| 3218.9 | $2^+$ | 3220 | $2^+$ | 3220.0 | $2^+$ | 3217 | $2^+$ | 3219 | $2^+$ | 3218 | $2^+$ | 3219 | $2^+$ |
| 3486.8 | $1^+$ | 3488 | $(1^+)$ | 3487.8 | $(^+)$ | 3483 | $(1, 2^+)$ | 3484 | $(1, 2^+)$ | 3485 | $(1, 2^+)$ | 3489 | $1^+$ |
| 3525 | $(1^+, 2^+)$ | ... | ... | ... | ... | ... | ... | 3598 | $(1, 2^+)$ | ... | ... | ... | ... |
| 3611.6 | $(1, 2)^+$ | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... |
| 3635.7 | $3^+$ | 3635 | $(3^+)$ | ... | ... | ... | ... | ... | ... | ... | ... | 3635 | $(3^+)$ |
| 3951.9 | $(3^\pm)$ | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... |
| 3966.3 | $(1^\pm, 2^+)$ | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... |
| 4037.3 | $(2^+)$ | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... |
| 4224.2 | $(3^\pm)$ | ... | ... | ... | ... | ... | ... | ... | ... | 4227 | $(3^+)$ | ... | ... |
| ... | ... | ... | ... | 4269.6 | ... | ... | ... | ... | ... | ... | ... | ... | ... |
| 4414.1 | $(2^+)$ | 4414 | $(3, 2^+)$ | 4413.9 | $(^-)$ | 4411 | $(2, 3, 4^+)$ | ... | ... | ... | ... | 4412 | $(3^+)$ |
| 4514.1 | $(2^-)$ | 4513 | $(2, 3^-)$ | 4513.9 | $(^-)$ | 4515 | $2^-$ | 4515 | $2^-$ | 4515 | $2^-$ | 4514 | $2^-$ |
| 4633.6 | $(2^+)$ | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... |
| 4743.7 | $(1^\pm, 2^+)$ | 4745 | $(2^+)$ | 4744.5 | $(^-)$ | 4740 | $(1)^-$ | 4742 | $(1^\pm, 2^+)$ | 4738 | ... | 4746 | $(1^-)$ |
| 4846.0 | $(3^-)$ | 4845 | $(3^-)$ | 4845.6 | $(3^-)$ | ... | ... | ... | ... | ... | ... | 4846 | $3^-$ |
| ... | ... | ... | ... | ... | ... | 4850 | $(3)^-$ | 4852 | $1^-$ | 4850 | $(2^-)$ | ... | ... |
| 4854.0 | $(1^-)$ | 4854 | $(2^-)$ | 4854 | $(^-)$ | ... | ... | ... | ... | ... | ... | 4855 | $2^-$ |

other experiments. The $\log_{10} ft$ value of 8.0 and the ground-state $\gamma$ decay of this level allow possible $1^{\pm}, 2^{+}$ assignments.

Our data for the level at 4037 keV are consistent with the data from the $(d, p)$ reaction[16] and the $(t, p)$ reaction,[15] which we believe are populating the same level. Consequently, we assign a spin-parity value of $2^{+}$.

The level at 4224 keV may be the same as the 4227-keV level populated in the $(n, \gamma)$ experiment[17] by an intense $\gamma$ transition from the capture state and assigned a $3^{-}$ spin-parity value. Our $\beta$- and $\gamma$-decay data are consistent with a $3^{-}$ assignment, although a $3^{+}$ value would also be compatible with both experiments.

Fed by $\beta$ decay with a $\log_{10} ft = 5.2$, the 4514-keV level is definitely of odd parity. Therefore, the 4514-keV level populated in the $(d, p)$ reaction cannot be the same one, since it is populated with an $l = 2$ neutron.

The level at 4634 keV appears to be the same as the one observed at 4636 keV from the $(d, p)$ reaction with an $l_n$ value of 2. The spin-parity value consistent with both experiments is $2^{+}$, since the ground-state transition rules out a possible $3^{+}$ assignment.

TABLE IV. Comparison of the population of $^{88}$Sr levels.

| $^{88}$Rb decay [a] | | $^{87}$Sr$(n, \gamma)$ [b] | | $^{87}$Sr$(d, p)$ [c] | | $^{86}$Sr$(t, p)$ [d] | | $^{87}$Rb$(^3$He$, d)$ [e] | | $^{88}$Sr$(p, p')$ [f] | | $^{89}$Y$(t, \alpha)$ [g] | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $E$ (MeV) | $J^{\pi}$ | $E$ (MeV) | $J^{\pi}$ | $E$ (MeV) | $l_n$ | $E$ (MeV) | $J^{\pi}$ | $E$ (MeV) | $l_p$ | $E$ (MeV) | $J^{\pi}$ | $E$ (MeV) | $l_p$ |
| 0 | $0^+$ | 0 | $0^+$ | 0 | 4 | 0 | $0^+$ | 0 | 1 | 0 | $0^+$ | 0 | 1 |
| 1.836 15 | $2^+$ | 1.8361 | $2^+$ | 1.839 | 2 | 1.836 | $2^+$ | 1.836 | 1 | 1.831 | $2^+$ | 1.836 | 1 |
| 2.734 18 | $3^-$ | 2.7341 | $3^-$ | 2.738 | ns [h] | 2.734 | $3^-$ | 2.734 | 4 | 2.744 | $3^-$ | ··· | ··· |
| ··· | ··· | ··· | ··· | ··· | ··· | 3.151 | $0^+$ | 3.155 | 1 | ··· | ··· | ··· | ··· |
| 3.2189 | $2^+$ | 3.2195 | $2^+$ | 3.208 | ns [h] | 3.220 | $2^+$ | 3.220 | 1 | 3.236 | $2^+$ | 3.221 | 1 |
| 3.4868 | $1^+$ | 3.4870 | $1^+$ | ··· | ··· | ··· | ··· | 3.489 | 1 | ··· | ··· | 3.489 | 1 |
| 3.525 | $(1^+, 2^+)$ | 3.5226 | $(2^+)$ | ··· | ··· | ··· | ··· | ··· | ··· | 3.514 | ··· | ··· | ··· |
| ··· | ··· | 3.5846 | $(4^-, 5^-)$ | (3.590) | ns [h] | ··· | ··· | 3.587 | 4 | ··· | ··· | ··· | ··· |
| 3.6116 | $(1, 2)^+$ | ··· | ··· | ··· | ··· | ··· | ··· | (3.606) | ··· | 3.607 | $2^+$ | ··· | ··· |
| 3.6357 | $3^+$ | 3.6352 | $3^+$ | ··· | ··· | ··· | ··· | (3.636) | ··· | ··· | ··· | 3.635 | ··· |
| 3.9519 | $(3^{\pm})$ | 3.9526 | $(4^+)$ | ··· | ··· | ··· | ··· | 3.955 | 4 | ··· | ··· | 3.946 | ··· |
| 3.9663 | $(1^{\pm}, 2^+)$ | ··· | ··· | ··· | ··· | ··· | ··· | (3.977) | ··· | 3.974 | $2^+$ | ··· | ··· |
| ··· | ··· | ··· | ··· | ··· | ··· | 3.990 | $(4^+, 3^-)$ | (3.997) | ··· | ··· | ··· | 3.985 | ··· |
| ··· | ··· | ··· | ··· | ··· | ··· | ··· | ··· | 4.020 | 4 | ··· | ··· | 4.029 | ··· |
| 4.0373 | $(2^+)$ | ··· | ··· | 4.035 | 2 | 4.033 | $2^+$ | (4.041) | ··· | 4.055 | $2^+$ | ··· | ··· |
| ··· | ··· | ··· | ··· | ··· | ··· | ··· | ··· | (4.152) | ··· | ··· | ··· | 4.154 | ··· |
| ··· | ··· | 4.1701 | $(4^-)$ | ··· | ··· | ··· | ··· | 4.173 | (4) | 4.178 | ··· | ··· | ··· |
| 4.2242 | $(3^{\pm})$ | 4.2273 | $(3^-)$ | ··· | ··· | 4.232 | $4^+$ | 4.231 | ··· | 4.234 | $3^-$ | ··· | ··· |
| ··· | ··· | 4.2693 | $(3^{\pm})$ | ··· | ··· | ··· | ··· | 4.271 | ··· | ··· | ··· | ··· | ··· |
| ··· | ··· | 4.3005 | $(4^+)$ | 4.294 | 2 | 4.298 | $4^+$ | (4.303) | ··· | 4.301 | $4^+$ | 4.287 | ··· |
| ··· | ··· | ··· | ··· | ··· | ··· | ··· | ··· | 4.355 | 4 | ··· | ··· | ··· | ··· |
| ··· | ··· | ··· | ··· | ··· | ··· | ··· | ··· | 4.374 | ··· | 4.367 | ··· | ··· | ··· |
| ··· | ··· | ··· | ··· | 4.408 | 2 | ··· | ··· | (4.397) | ··· | ··· | ··· | ··· | ··· |
| 4.4141 | $(2^+)$ | 4.4139 | $(3^+)$ | ··· | ··· | 4.416 | $\{2^+, 6^+\}$ | 4.417 | ··· | 4.418 | ··· | ··· | ··· |
| ··· | ··· | ··· | ··· | 4.450 | 2 | ··· | ··· | ··· | ··· | 4.438 | ··· | 4.428 | ··· |
| ··· | ··· | 4.4520 | $(3^-, 4^-)$ | 4.464 | ns [h] | ··· | ··· | 4.455 | ··· | ··· | ··· | ··· | ··· |
| ··· | ··· | ··· | ··· | ··· | ··· | 4.484 | $0^+$ | 4.481 | ··· | ··· | ··· | ··· | ··· |
| 4.5141 | $(2^-)$ | 4.5138 | $(2^-, 3^-)$ | 4.514 | 2 | ··· | ··· | ··· | ··· | 4.520 | ··· | ··· | ··· |
| ··· | ··· | ··· | ··· | 4.551 | ··· | ··· | ··· | (4.606) | ··· | ··· | ··· | 4.607 | ··· |
| 4.6336 | $(2^+)$ | ··· | ··· | 4.636 | 2 | 4.619 | $2^+$ | 4.627 | 1 | 4.637 | ··· | ··· | ··· |
| ··· | ··· | ··· | ··· | ··· | ··· | ··· | ··· | (4.644) | ··· | ··· | ··· | ··· | ··· |
| 4.7437 | $(1^{\pm}, 2^+)$ | 4.7430 | $(2^+)$ | 4.748 | 2 | 4.763 | $2^+$ | (4.765) | ··· | 4.743 | ··· | 4.751 | ··· |
| ··· | ··· | ··· | ··· | 4.789 | ··· | 4.794 | $0^+$ | ··· | ··· | 4.777 | $2^+$ | ··· | ··· |
| 4.8460 | $(3^-)$ | 4.8456 | $(3^-)$ | ··· | ··· | 4.838 | $(3^-)$ | ··· | ··· | 4.864 | $(3^-)$ | ··· | ··· |
| 4.8540 | $(1^-)$ | ··· | ··· | ··· | ··· | ··· | ··· | ··· | ··· | ··· | ··· | ··· | ··· |

[a] This work.
[b] Reference 17.
[c] Reference 16.
[d] Reference 15.
[e] Reference 18.
[f] Reference 19.
[g] Reference 20.
[h] Nonstripping distributions.

## V. DISCUSSION

The levels of $^{88}$Sr populated by $\beta$ decay of $^{88}$Rb have been discussed earlier by one of the authors (RCR),[1] and we shall include in this report only those points of theoretical interest which supplement the earlier discussion. The $2^-$ ground state of $^{88}$Rb is assumed to be a linear combination of three proton holes in a $^{90}$Zr core coupled with an odd $2d_{5/2}$ neutron. The level structure energetics of the odd rubidium isotopes and magnetic-moment data[1] indicate that the $\pi(2p_{3/2})^{-1}\nu(2d_{5/2})$ coupling predominates, with two of the holes coupled to zero; the remainder is mostly $\pi(1f_{5/2})^{-1}\nu(2d_{5/2})$. In support of this experimental evidence, Shreve[18] has calculated the ground state of $^{87}$Rb to be 85% $(2p_{3/2})^{-1}$ by using the shell-model calculations of Hughes.[10] Therefore, the decay of the $2d_{5/2}$ neutron in $^{88}$Rb should preferentially populate 1p-3h proton components in the $^{88}$Sr excited states, where the odd hole is in either the $2p_{3/2}$ or $1f_{5/2}$ orbital.

Table V compares our results with shell-model calculations[10] of the neutron $(1g_{9/2})^{-1}(2d_{5/2})$ couplings for $^{88}$Sr and of the even-parity states produced by coupling two proton holes in the $Z=40$ subshell orbitals $1f_{7/2}$, $1f_{5/2}$, $2p_{3/2}$, and $2p_{1/2}$.

From analysis of the reactions $^{89}$Y($d$, $^3$He) and $^{88}$Sr($d$, $^3$He), Shreve[21] estimates that the ground state of $^{88}$Sr is mixed and the two-hole core configuration comprises about 60–80% of the wave function with the remaining strength consisting of 1p-3h couplings. These findings agree qualitatively with the calculations[10] which predict that the $\pi(2p_{1/2})^{-2}$ component comprises 69% of the wave function.

The experimental $\log_{10}ft$ values (7.8 and 7.5) for the population of the $2_1^+$ and $2_2^+$ levels suggest similar level composition. These results are consistent with the reaction data and with Hughes's calculations[10] which show that the bulk of the level strength is composed of the two proton couplings $(2p_{1/2})^{-1}(1f_{5/2})^{-1}$ and $(2p_{1/2})^{-1}(2p_{3/2})^{-1}$, with the former predominating (58%) in the $2_1^+$ level and the latter predominating (62%) in the $2_2^+$ level. Shastry,[11] on the other hand, can account for neutron 1p-1h components in his calculations, which predict that the $(2d_{5/2})(1g_{9/2})^{-1}$ coupling comprises 5% of the $2_1^+$ strength and 57% of the $2_2^+$ strength.

The ($^3$He, $d$) data of Shreve[18] show that 60–70% of the $^{88}$Sr $3_1^-$ octupole state at 2734 keV corresponds to the coupling of a $1g_{9/2}$ proton to the $^{87}$Rb ground state. This finding agrees qualitatively with the calculations of Shastry[11] which predict that the $\pi(1g_{9/2})(2p_{3/2})^{-1}$ component comprises 92% of the collective-state wave function which is constructed from a total of 14 1p-1h proton and three 1p-1h neutron components (Shastry uses a core of 38 protons in his calculations). Beres and Doren-

TABLE V. Comparison of calculated (Ref. 10) levels of $^{88}$Sr with those levels populated in $^{88}$Rb $\beta$ decay.

| Two proton holes in $Z=40$ subshell | | | $^{88}$Rb decay | | Neutron 1p-1h $\nu(2d_{5/2})(1g_{9/2})^{-1}$ | |
|---|---|---|---|---|---|---|
| Orbitals[a] | $E$ (MeV) | $J^\pi$ | $E$ (MeV) | $J^\pi$ | $E$ (MeV) | $J^\pi$ |
| $(2p_{1/2})^{-2}$ | 0 | $0^+$ | 0 | $0^+$ | | |
| $(2p_{3/2})^{-1}(2p_{1/2})^{-1}$ | 1.90 | $2^+$ | 1.836 | $2^+$ | | |
| $(1g_{9/2})(2p_{3/2})^{-1}$ | | | 2.734 | $3^-$ | | |
| $(2p_{1/2})^{-1}(1f_{5/2})^{-1}$ | 3.33 | $2^+$ | 3.218 | $2^+$ | | |
| | | | 3.487 | $1^+$ | | |
| $(1f_{5/2})^{-2}$ | 3.55 | $0^+$ | 3.525 | $(1^+, 2^+)$ | | |
| $(2p_{1/2})^{-1}(2p_{3/2})^{-1}$ | 3.58 | $1^+$ | 3.612 | $(1, 2)^+$ | | |
| | | | 3.635 | $3^+$ | | |
| $(2p_{1/2})^{-1}(1f_{5/2})^{-1}$ | 3.80 | $3^+$ | | | | |
| $(1g_{9/2})(1f_{5/2})^{-1}$ | | | 3.952 | $(3^\pm)$ | | |
| | | | 3.966 | $(1^\pm, 2^+)$ | | |
| | | | 4.037 | $(2^+)$ | | |
| | | | 4.224 | $(3^\pm)$ | 4.24 | $2^+$ |
| | | | 4.414 | $(2^+)$ | | |
| $(2p_{3/2})^{-1}(1f_{5/2})^{-1}$ | 4.55 | $4^+$ | 4.514 | $(2^-)$ | 4.52 | $4^+$ |
| | | | 4.634 | $(2^+)$ | 4.65 | $6^+$ |
| | | | 4.744 | $(1^\pm, 2^+)$ | | |
| | | | 4.846 | $(3^-)$ | 4.80 | $3^+$ |
| $(2p_{3/2})^{-2}$ | 4.86 | $6^+$ | 4.854 | $(2^-)$ | 4.91 | $5^+$ |
| $(1f_{5/2})^{-2}$ | 5.18 | $2^+$ | | | | |
| $(2p_{3/2})^{-1}(1f_{5/2})^{-1}$ | 5.23 | $1^+$ | | | 5.24 | $7^+$ |

[a] Principal components of calculated levels. Couplings involving the one $1g_{9/2}$ orbital were not included in calculations. The $1g_{9/2}$ couplings shown are from comparisons with other experimental data.

busch[9] have pointed out that the $\beta$ decay to the $3^-$ level is extremely sensitive to the amplitude of the neutron component $(2d_{5/2})(2p_{1/2})^{-1}$ in the $3^-$ wave function. Only by including neutron 1p-1h states and, in particular, an amplitude of 0.1 for the $\nu(2d_{5/2})(2p_{1/2})^{-1}$ term could they calculate the amount of $\beta$-decay hindrance necessary to reproduce the experimental $\log_{10}ft$ value. The higher couplings $(4^-, 5^-, 6^-)$ of the $\pi(1g_{9/2})(2p_{3/2})^{-1}$ configurations are not, of course, populated in any observable intensity by $^{88}$Rb $\beta$ decay, but they are plainly seen and identified in both the $(n,\gamma)$ reaction[17] and $(^3\mathrm{He}, d)$ reaction.[18]

The $1_1^+$ and $3_1^+$ states are calculated to originate exclusively (99%) from the $\pi(2p_{1/2})^{-1}(2p_{3/2})^{-1}$ and $\pi(2p_{1/2})^{-1}(1f_{5/2})^{-1}$ couplings,[10] respectively, and our $\log_{10}ft$ values of 8.0 and 8.5 are consistent with this interpretation. As the $^{88}$Rb ground state contains more $\pi(2p_{3/2})^{-1}$ than $\pi(1f_{5/2})^{-1}$, it is consistent to have more feeding to the $1_1^+$ level than to the $3_1^+$ level. Too little data are available on the 3525-, 3612-, and 3966-keV levels to permit any comparisons with theoretical calculations.

The spectrum above 4 MeV becomes very complicated because the neutron pairing energy is exceeded, and 1p-1h neutron states become energetically possible. The 4037- and 4414-keV $2^+$ levels are composed in part of the neutron configuration $(2d_{5/2})(1g_{9/2})^{-1}$. Both levels are observed in the $(t, p)$ reaction results,[15] where it was pointed out that the 4408-keV level reported by Cosman and Slater[16] is very likely the $6^+$ coupling of the $(2d_{5/2})(1g_{9/2})^{-1}$ configuration and not the $2^+$ level at 4414 keV. The 4037-keV level appears to contain most of the strength of the $\nu[(2d_{5/2})(1g_{9/2})^{-1}]_{2^+}$ coupling, while the 4414-keV level evidently has significant proton 1p-3h character. The large difference in the $\beta$-transition intensities to these two levels is consistent with the very different parentages postulated above.

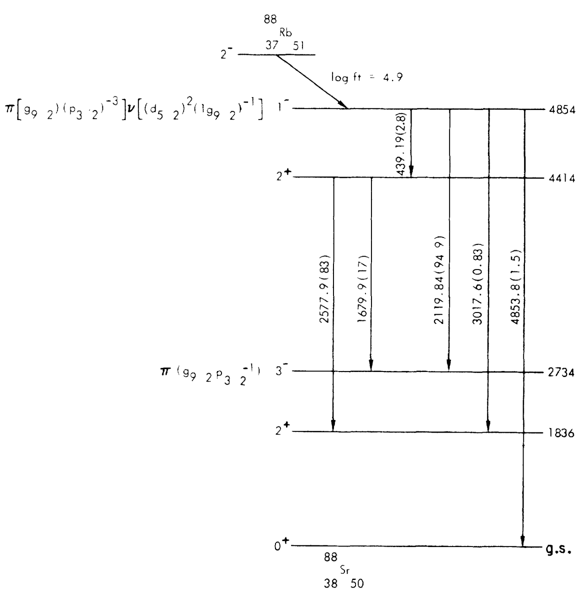


FIG. 4. Partial decay scheme showing decay properties of the proposed two-particle–four-hole state at 4854 keV.

Since the $2^-$ level at 4514-keV is not appreciably populated in the $(^3\mathrm{He}, d)$ reactions, and since it is of odd parity, it most likely consists of the $\nu(2d_{5/2})(2p_{3/2})^{-1}$ configuration and/or the $\nu(2d_{5/2})(2p_{1/2})^{-1}$ configuration. Both configurations are consistent with the low $\log_{10}ft$ value of 5.2. As the 4846-keV $3^-$ level is populated in the $(t, p)$ reaction, we conclude that these neutron 1p-1h configurations are also significant in its wave function.

The $1^-$ level at 4854 keV possesses a large $\gamma$-transition probability for decay into the one-octupole-phonon 2734-keV state and a low $\log_{10}ft$ value for population by $\beta$ decay from $^{88}$Rb. A detail of the decay properties of this level is shown in Fig. 4. The 2119-keV $E2$ transition to the 2734-keV level is 62 times more intense than the 4854-keV $E1$ transition to the ground state. The single-particle estimates for these transitions predict a branching ratio of $E2/E1 = 10^{-6}$ instead of 62. Regardless of the degrees of $E2$ enhancement, this requires a considerable hindrance of the $E1$. We should not expect that the $E2$ would be enhanced more than the $E2$ depopulating the first $2^+$ level at 1836 keV, which appears to be enhanced by only a few single-particle units. This limitation of $E2$ enhancement would require that the 4853-keV $E1$ transition be hindered by at least a factor of $10^{-5}$. The other $E1$ transitions that have been assigned to the decay of this level are the 439.19- and 3017.6-keV $\gamma$ rays. If we normalize the relative reduced transition probabilities to the 439.19-keV $\gamma$ ray we obtain a ratio for 439 : 3017 : 4853 of $1.0 : 9\times10^{-4} : 4\times10^{-4}$ which is consistent with a hindered nature of the 4853-keV transition. The low $\log_{10}ft$ value of 4.9 indicates that the level does not have collective character and therefore is not a coupled quadrupole-octupole phonon level. Rather it is quite likely that the 4854-keV level is closely related to the 1p-3h configurations which make up the $^{88}$Rb parent. The most probable wave function postulated for this level is of 2p-4h character:

$$\pi[(1g_{9/2})(2p_{3/2})^{-3}]\,\nu[(2d_{5/2})(1g_{9/2})^{-1}]\,.$$

The $\beta$ decay into such a configuration would be represented by decay of a $1g_{9/2}$ neutron into a $1g_{9/2}$ proton, easily accounting for the low $\log_{10}ft$ value. The $E2$ $\gamma$ decay to the $3_1^-$ level would involve basically reconfiguring the $(2d_{5/2})(1g_{9/2})^{-1}$

neutrons to the closed-shell configuration. The strongly hindered $E1$ $\gamma$ decay would proceed via small admixtures in the wave functions of parent and daughter levels.[22]

A still unresolved question is the location of the first $^{88}$Sr $4^+$ level, the $4^+$ member of the two-quadrupole-phonon multiplet of spherical vibrators. Lycklama and Kennett[17] report the $4_1^+$ level as occurring at 3953 keV on the basis of their $(n,\gamma)$ reaction data. However, as discussed earlier, more recent evidence seems to favor a $3^\pm$ assignment. Ragaini, Knight, and Leland[15] propose that a level at $3990 \pm 5$ keV populated in the $(t, p)$ reaction is either $4^+$ or $3^-$. While the $(^3\mathrm{He}, d)$ reaction results[18] show a level at $3997 \pm 7$ keV, no spin-parity information exists. Since there is insufficeint direct evidence, a definite spin-parity assignment is not possible, although, as pointed out previously,[15] an indirect argument can be made. The nonpopulation (or very weak population) of this 3990-keV level in $^{88}$Rb $\beta$ decay is reasonable evidence that an allowed $\beta$ transition does not occur, and thus the $4^+$ assignment, rather than $3^-$, is most probably the correct one. The next higher $4^+$ level occurs at 4232 keV and is populated in the $(t, p)$ reaction.

Hughes[10] predicts a $4^+$ level at 4.55 MeV primarily comprising the $\pi[(2p_{3/2})^{-1}(1f_{5/2})^{-1}]_{4^+}$ coupling and a $4^+$ level at 4.52 MeV from the $\nu(2d_{5/2})(1g_{9/2})^{-1}$ coupling. According to the variable-moment-of-inertia model,[23] the $R_4(E_{4^+}/E_{2^+})$ value for $^{88}$Sr is consistent with values for spherical nuclei. In comparison the $R_4$ value for $^{90}$Zr is 1.41, a smaller $R_4$ value, which is more indicative of single and double magic nuclei. For $^{92}$Mo the $R_4$ value is 1.51. Scharff-Goldhaber and Goldhaber[23] have pointed out that the experimental $R_4$ values should have particle-hole symmetry relative to closed shells; therefore, on this basis the $^{88}$Sr $R_4$ value should be approximately 1.51, which would place the $4_1^+$ level at 2.772 MeV in $^{88}$Sr. However, such comparisons are not appropriate in this mass region because the $\pi(g_{9/2})^2$ couplings dominate the low-energy structure of $^{90}$Zr and $^{92}$Mo, whereas for $^{88}$Sr the $\pi(g_{9/2})^2$ couplings would lie at higher energies and therefore would have a lesser influence on the $4_1^+$ level position.

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