Decay of ^{84}Br†

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The decay of ^{84}Br to levels in ^{84}Kr was investigated using Ge(Li) and NaI(Tl) γ detectors. On the basis of energy, intensity, and coincidence measurements a new decay scheme including 20 levels is proposed. Out of a total of 51 γ rays observed, all but 3 were placed in the level scheme. The level scheme includes states at 1837, 2489, 3870, 3879, and 4189 keV not seen in previous decay studies. Spin assignments were made for most levels based on our γ-intensity measurements and log*ft* values. The level scheme is compared with the results of recent $(\alpha, 2n\gamma)$ and (p,t) reaction studies.

I. INTRODUCTION

The level structure of ^{84}Kr has been studied from the β decay of both ^{84}Br and ^{84}Rb. Because of the low Q value for ^{84}Rb decay the only excited states populated[1,2] were the 2^+ levels at 882 and 1898 keV. The decay of ^{84}Br was studied by Johnson and O'Kelley[3] using NaI detectors. Their decay scheme included levels up to 4.18 MeV. During the course of our study a decay scheme of ^{84}Br was published by Hattula *et al.* (HASM)[4] using Ge(Li) and β detectors. They also studied the decay of the 6.0-min high-spin isomeric state of ^{84}Br. The levels of ^{84}Kr have also been studied by Coulomb excitation,[5] $(\alpha, 2n\gamma)$,[6] and (p, t)[7] reactions.

In the present work we investigated the decay of the ^{84}Br ground state ($\tau_{1/2} = 31.8$ min)[4] to levels in ^{84}Kr using Ge(Li) detectors and coincidence techniques. In Sec. II the experimental procedures and results are described. The construction of the decay scheme is discussed in Sec. III. A comparison of our results with the work of others and our conclusions are summarized in Sec. IV.

II. EXPERIMENTAL

A. Source Preparation

About 200 mg of natural uranyl acetate were irradiated for 30 min in a thermal-neutron flux of 2×10^{12} n/cm^2 sec from the Texas A&M University TRIGA reactor. After irradiation a waiting period of 15 min permitted decay of short-lived Br fission products. The sample was then dissolved in H_2O, and Br was oxidized to the elemental form with $KMnO_4$ and extracted into CCl_4 to effect its separation from most other fission products. The Br was next reduced to Br^- with $NaHSO_3$ and I was separated by oxidation to the elemental form with $NaNO_2$ and extraction into CCl_4. The Br^- was precipitated as AgBr, filtered, and mounted for counting. The ^{84}Br was ready for counting 40 min after the end of the irradiation. No fission product impurities other than ^{83}Br were observed. The time elapsed during chemical processing was sufficient to eliminate the 6-min isomeric state of ^{84}Br.

B. γ Energies

The γ spectrum was measured using a 55-cm^3 Ge(Li) detector having a low counting-rate resolution [full width at half maxium (FWHM)] of 2.6 keV for the 1332-keV γ ray from ^{60}Co. The data were stored in a 4096-channel analyzer. In typical runs sources were changed about every 2 h. A total counting time of 12 h per spectrum was typical. A γ spectrum for ^{84}Br is shown in Fig. 1. The low- and high-energy portions of the spectrum were collected in separate runs. The 530-keV transition from ^{83}Br and the 1294-keV transition from ^{41}Ar produced near the reactor were the only lines definitely not attributable to ^{84}Br decay. Both lines were long-lived compared to ^{84}Br lines. Very weak γ peaks were observed at 1143 and 1780 keV, but it was impossible to determine from their half-lives whether they originated from ^{84}Br decay. The details of the partially resolved peaks [948 + 956], [$(2824)_2$ + 1808], and [$(3045)_2$ + 2030] keV are shown in the insets in Fig. 1. Single- and double-escape peaks are designated by subscripts 1 and 2, respectively. The region around 1290 keV is also shown in an inset. Doublets at [1006 + $(2030)_2$] and [$(2484)_2$ + 1464] keV were too closely spaced to be separable. No γ rays of energy less than 230 keV associated with ^{84}Br decay were observed. No evidence for significant coincidence summing was seen.

The energies of prominent ^{84}Br γ rays were measured using standard lines from ^{57}Co, ^{203}Hg, ^{51}Cr, ^{198}Au, ^{22}Na, ^{88}Y, ^{24}Na, ^{228}Th, ^{60}Co, and the 4945-keV neutron-capture γ ray from carbon. The prominent ^{84}Br γ rays were used as secondary standards to determine the energy of weaker γ rays in both singles and coincidence spectra. The position of each photopeak was obtained from a Gaussian fit after visual subtraction of the Compton background. The calibration energies were fitted to a second-order polynomial. The energies and errors of all γ transitions are given in Table I. The 1006- and 1464-keV γ rays are members of closely spaced doublets; thus the errors of their energies are relatively large. The energies of several weak transitions were obtained from coincidence spectra.

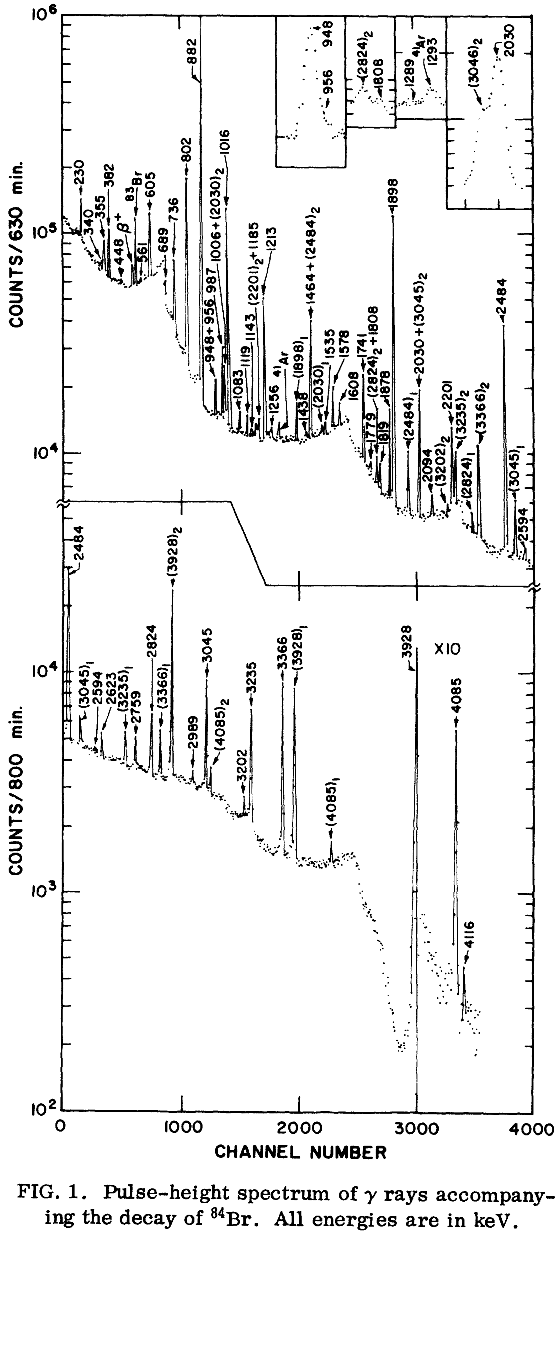

FIG. 1. Pulse-height spectrum of γ rays accompanying the decay of ^{84}Br. All energies are in keV.

C. γ Intensities

Relative γ intensities were determined using the Ge(Li) detector and are given in Table I. The efficiency for the detector was obtained by a pair point method[8] using $^{180m}Hf^*$, ^{133}Ba, ^{24}Na, ^{60}Co, ^{88}Y, ^{22}Na, ^{207}Bi, ^{56}Co, and ^{46}Sc as standards. Upper limits on the intensity of γ rays at 1289, 1970, and 2304 keV observed by HASM but not seen in this work was given in Table I. Details of the singles spectrum at 1289 keV are shown in the inset in Fig. 1. The energy of the peak near 1289 keV has an energy of 1293.7 ± 0.4 keV and a half-life longer than that of neighboring ^{84}Br lines. We thus attribute this peak to ^{41}Ar. Its energy agrees with a recently determined value[9] of 1293.64 ± 0.04 keV. The peak at 1973 keV was attributed to the single-escape peak of the 2484-keV γ ray on the basis of its energy and intensity. No evidence was seen for a doublet at this energy as reported by HASM. Details of the peak at about 950 keV are also shown in an inset in Fig. 1. An expanded linear count-rate scale is used to show the detail. The width (FWHM) of the peak is larger than other peaks in this energy region and it has a significant tail on the high-energy side. We interpret the peak to be a doublet composed of a strong 948-keV γ ray and a weak 956-keV γ ray. The 394-keV γ ray was not observed in the singles spectrum; thus its intensity could not be determined owing to uncertainty concerning its placement in the level scheme.

D. γ-γ Coincidences

Measurements of γ-γ coincidences were performed using a 3×3-in. NaI(Tl) detector and the Ge(Li) detector. The pulse from the NaI(Tl) detector was used to gate the analyzer. The axes of the detectors were oriented at 180° to each other, and a coincidence resolving time of 90 nsec was used.

The spectrum observed in coincidence with the 882-keV γ ray is shown in the upper half of Fig. 2. All peaks shown were in cascade with the 882-keV transition except for the 882- and 1898-keV γ rays. The spectrum observed in coincidence with the 1898-keV γ ray is shown in the lower half of Fig. 2. Transitions at 230, 355, 382, 394, 448, 736, 802, 1006, 1185, 1578, 1808, 2030, and 2218 keV are in cascade with the 1898-keV γ ray. Transitions at 882, 948, and 1119 keV are in cascade with the 1878-keV γ ray. Other peaks observed are primarily due to chance coincidences.

The spectrum observed in coincidence with the 1213-keV γ ray is shown in the upper half of Fig. 3. Transitions at 382, 605, 882, 987, 1006, and 2094 keV are in cascade with the 1213-keV γ ray. Transitions at 394 and 689 keV were seen more strongly in this spectrum than any other. The presence of the 1741-keV peak is due to its coincidence with the 1256-keV γ ray. Other peaks observed were due to coincidences with Compton events in the gate from γ rays of energy greater than 1300 keV.

The spectrum observed in coincidence with the 1464-keV γ ray is shown in the lower half of Fig. 3. Transitions at 355, 382, 736, 882, and 1006 keV were in cascade with the 1464-keV γ ray. There is weak evidence for a coincident peak at 1535 keV. Other peaks can be attributed to coincidences with Compton events in the gate or chance coincidences.

The spectrum observed in coincidence with all γ rays above 2200 keV is shown in Fig. 4. Transitions observed in coincidence with γ rays above 2200 keV were observed at 230, 340, 561, 882, 948, 1016, 1083, 1119, and 1898 keV. The 1143-keV γ ray was prominent in the above spectrum, but its position in the level scheme could not be determined. It was not observed in a coincidence run gating γ rays above 2800 keV. Other peaks in the spectrum in Fig. 4 were due to chance coincidences and events in coincidence with the high-energy tail of the strong 1898-keV γ ray in our gate.

A typical γ spectrum for ^{84}Br measured using a 3-in.×3-in. NaI(Tl) detector is shown in Fig. 5. Pulses from the NaI(Tl) detector were used to gate the analyzer in the various coincidence runs. The gate widths used for the 882-, 1898-, 1213-, and 1464-keV coincidence spectra are designated (a), (d), (b), and (c), respectively. The low-energy limit of the gate used in observing coincidences with high-energy γ rays is designated e. The gate purity has been discussed in some detail above for each coincidence spectrum. The 882-keV coincidence spectrum is almost completely dominated by γ rays in coincidence with the strong 882-keV transition, and the only significant impurity

TABLE I. γ-ray energies and relative intensities.

Energy (keV)	Relative intensity [a]	Level (keV) (from-to)	Energy (keV)	Relative intensity [a]	Level (keV) (from-to)
230.2 ± 0.2	0.73 ± 0.1	3706-3476	1534.7 ± 0.6	0.24 ± 0.05	3879-2345
339.8 ± 0.4	0.17 ± 0.04	3706-3366	1578.1 ± 0.4	1.56 ± 0.3	3476-1898
354.7 ± 0.2	0.73 ± 0.1	2700-2345	1607.6 ± 0.4	0.95 ± 0.15	2489-882
382.0 ± 0.2	1.35 ± 0.2	3082-2700	1741.2 ± 0.4	3.9 ± 0.6	2623-882
		2489-2095	1779.6 ± 0.7	0.15 ± 0.04	Not placed
394.1 ± 0.7 [b]		3476-3082	1807.8 ± 0.8 [d]	0.10 ± 0.03	3706-1898
		3870-3476	1818.7 ± 0.4	0.58 ± 0.09	2700-882
447.7 ± 0.8	0.10 ± 0.03	2345-1898	1877.5 ± 0.4	2.7 ± 0.4	2759-882
561.4 ± 0.5 [c]	0.20 ± 0.05	3927-3366	1897.6 ± 0.2	35.4 ± 3.5	1898-0
604.8 ± 0.3	4.2 ± 0.6	2700-2095	1970 [e]	<0.15 [e]	
688.7 ± 0.7 [b]	0.22 ± 0.06	Not placed	2029.6 ± 0.5	5.0 ± 1.0	3927-1898
736.5 ± 0.3	3.1 ± 0.5	3082-2345	2094.2 ± 0.5	0.51 ± 0.1	4189-2095
802.2 ± 0.2	14.4 ± 1.5	2700-1898	2200.7 ± 0.4	2.8 ± 0.4	3082-882
881.6 ± 0.1	100 [a]	882-0	2218.5 ± 1.2 [d]	0.16 ± 0.08 [d]	4116-1898
947.5 ± 0.7	0.85 ± 0.2	3706-2759	2304 [e]	<0.1 [e]	
955.7 ± 2.0	0.15 ± 0.07	1837-882	2484.1 ± 0.3	16.0 ± 1.6	3366-882
987.3 ± 0.4	1.85 ± 0.3	3082-2095	2593.7 ± 0.6	0.33 ± 0.07	3476-882
1005.7 ± 0.7	1.09 ± 0.3	3706-2700	2622.9 ± 0.5	0.72 ± 0.15	2623-0
1015.9 ± 0.3	14.8 ± 1.5	1898-882	2758.7 ± 0.5	1.17 ± 0.2	2759-0
1082.6 ± 0.4	0.34 ± 0.06	3706-2623	2824.1 ± 0.4	2.7 ± 0.4	3706-882
1119.1 ± 0.4	0.34 ± 0.06	3879-2759	2988.7 ± 0.7	0.42 ± 0.1	3870-882
1142.7 ± 1.0 [c]	0.079 ± 0.03	Not placed	3045.4 ± 0.4	6.0 ± 0.9	3927-882
1185.0 ± 0.7 [d]	0.26 ± 0.05	3082-1898	3202.1 ± 0.7	0.50 ± 0.1	4084-882
1213.3 ± 0.2	6.2 ± 0.7	2095-882	3235.3 ± 0.5	4.9 ± 0.8	4116-882
1255.5 ± 0.6	0.11 ± 0.02	3879-2623	3365.8 ± 0.4	6.9 ± 1.0	3366-0
1289 [e]	<0.04 [e]		3927.5 ± 0.4	16.3 ± 1.7	3927-0
1438.0 ± 0.7	0.15 ± 0.04	3927-2489	4084.6 ± 0.6	0.66 ± 0.1	4084-0
1463.8 ± 0.7	4.7 ± 0.9	2345-882	4115.8 ± 1.5	0.0093 ± 0.002	4116-0

[a] Intensities normalized to 100 for the 882-keV γ ray.
[b] From the 1213-keV coincidence spectrum.
[c] From the high-energy coincidence spectrum.
[d] From the 1898-keV coincidence spectrum.
[e] Upper limit on intensity of transition observed by others.

in the 1898-keV gate is from the 1878-keV γ ray. The 1213- and 1464-keV gates contain a large number of events from the Compton distribution of the 1898-keV γ ray, and the gate for γ rays above 2200 keV includes some events from the tail of the 1898-keV photopeak which are significant because of the small number of γ rays in coincidence with high-energy γ transitions.

III. DECAY SCHEME

The γ-transition energies and intensities and their coincidence relationships have been interpreted on the basis of the decay scheme shown in Fig. 6. All levels observed by HASM were confirmed with the exception of the level at 2171 keV. We postulate new levels at 2489, 3870, 3879, and 4189 keV. The β^- decay of ^{84}Br probably populated a 0^+ level at 1837 keV seen in the (p, t) reaction.[7] The energy of the 394-keV γ ray corresponds to three possible transitions in the level scheme. The $\log ft$ values for β decay to levels in ^{84}Kr were determined from γ intensities obtained in this work. The relative intensity of the β branch to the ground state was taken to be 33% from the work of HASM,

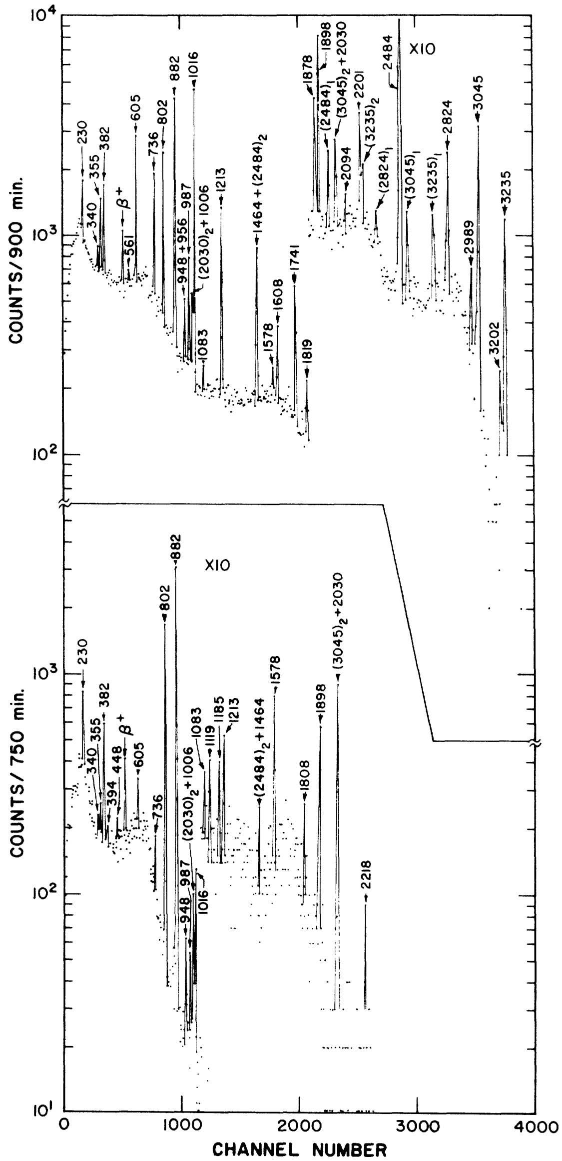

FIG. 2. Pulse-height spectrum of γ rays in coincidence with the 882-keV γ ray (upper half) and the 1898-keV γ ray (lower half). All energies are in keV.

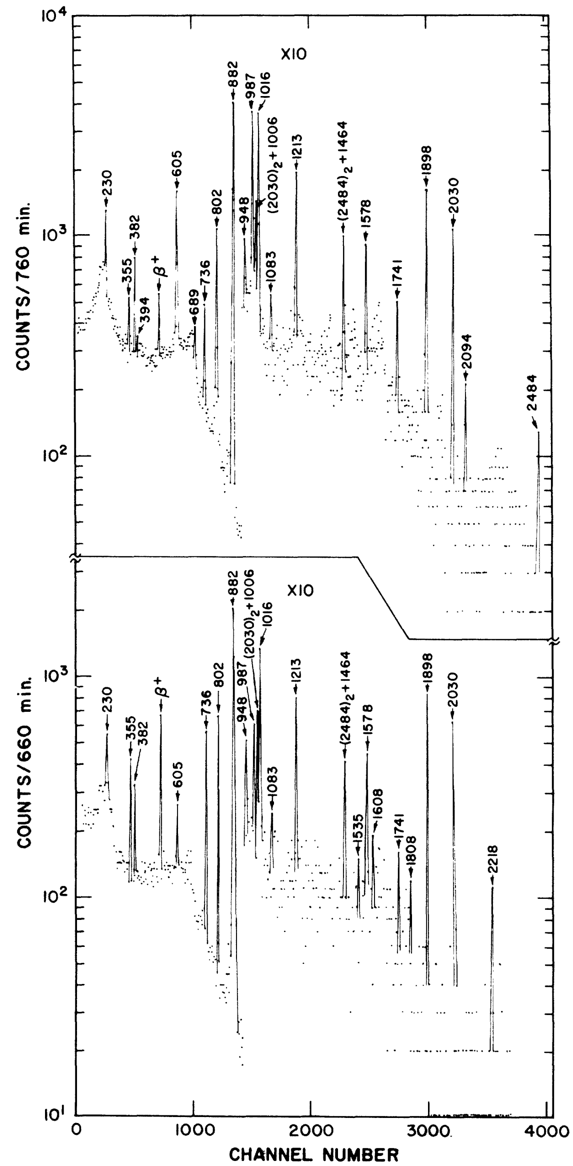

FIG. 3. Pulse-height spectrum of γ rays in coincidence with the 1213-keV γ ray (upper half) and the 1464-keV γ ray (lower half). All energies are in keV.

which agrees with a value of 32% obtained by Johnson and O'Kelley.[3] The logft's have not been corrected for internal conversion. This correction is small except possibly for the 3082- and 3476-keV levels. Logf_1t's were calculated for each level. For a logf_1t less than 7.6 the Nuclear Data Group has established[10] that the corresponding β transition cannot be first-forbidden unique; therefore a spin change of less than 2 is involved. A discussion of the energies, spins, and parities of the individual levels follows.

Ground state. The assignment for the ^{84}Kr ground state is 0^+ as for all even-even nuclei. An assignment of 2^- for the ^{84}Br ground state was given by HASM from shape measurements of the β^- group feeding the ^{84}Kr ground state. This assignment was used in limiting the spins of several excited states of ^{84}Kr. Our logft of 7.7 for the ground state is consistent with that of Johnson and O'Kelley,[3] but not with the value of 8.3 obtained by HASM.

881.6 ± 0.1-keV level. The energy of this level is that of the 882-keV γ ray. Its assignment of 2^+ is from Coulomb excitation[5] using 6.6-MeV α particles.

1837.3 ± 0.8-keV level. The energy of this level was determined from the energies of the 882- and 956-keV γ rays. Other placements of the 956-keV γ ray consistent with the coincidence data are possible; thus the level is dashed on the level scheme. Our placement is supported by the work of Levine,[7] who observed a 0^+ level at 1835 keV populated in the (p, t) reaction. Our rather high logft of 9.5 is consistent with the 0^+ assignment.

1897.6 ± 0.2-keV level. The level energy was determined from an average of the 1898-keV transition energy and the sum of the energies of the 882- and 1016-keV transitions. The 2^+ assignment is based on γ-γ angular correlations[1] of the 1016 + 882-keV cascade following the decay of ^{84}Rb.

2094.9 ± 0.3-keV level. The energy of this level was determined from the energies of the 882- and 1213-keV γ rays. McCauley and Draper[6] determined this state to be the 4^+ yrast level from the angular distribution and intensity of the 1213-keV γ ray emitted in the $(\alpha, 2n\gamma)$ reaction on a ^{82}Se target. Our β^- feeding to the level is zero within

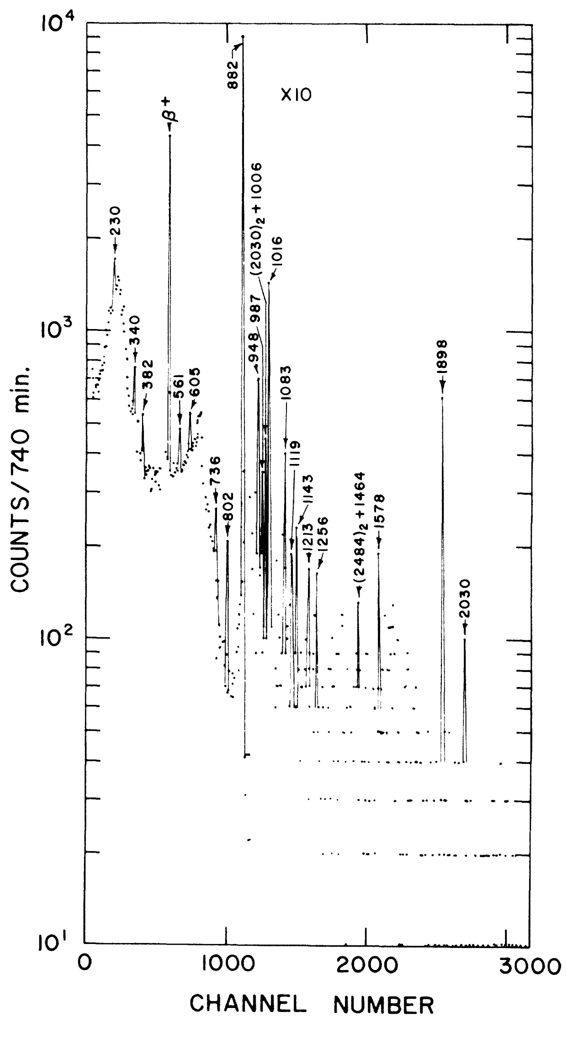

FIG. 4. Pulse-height spectrum of γ rays in coincidence with γ rays above 2200 keV. All energies are in keV.

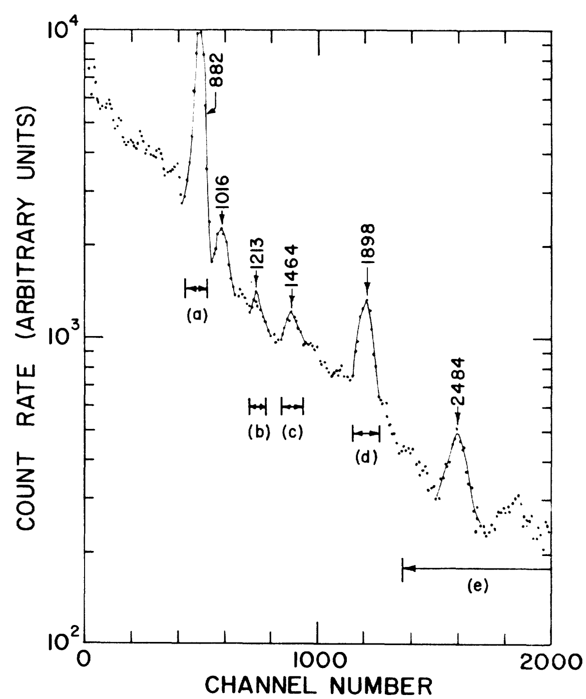

FIG. 5. Typical pulse-height spectrum of γ rays from the NaI(Tl) detector. Widths of gates [(a)–(e)] used in the various coincidence runs are indicated.

the error of the intensity measurements. This result implies a high logft and is consistent with a 4^+ assignment.

A 0^+ level at 2171 keV was postulated by HASM on the basis of a transition at 1289 keV going to the first excited 2^+ state. They measured the 1289-keV γ ray to have an intensity of 0.4. We place an upper limit of 0.04 on its intensity. We did observe a background γ ray at 1294 keV which was attributed to ^{41}Ar produced near the reactor because of its long half-life.

2345.4 ± 0.6-keV level. The energy of this level was determined from an average of the cascade energies through the 1898- and 882-keV levels. The two cascade energies differ by only 0.1 keV, but our level energy is somewhat higher than the value of 2344.5 keV obtained by HASM. The logft of 8.4 allows the possibility of any spin between 0 and 4.

2489.2 ± 0.5-keV level. The energy of this new level was determined from the sum of the energies of the 1608- and 882-keV γ rays. Its existence is based on the strong coincidence of the 1608-keV γ ray with the 882-keV transition. The weak 1608-keV peak in the 1464-keV coincidence spectrum is due to the 1438-keV γ ray feeding the 2489-keV level. The 1608-keV γ ray is too strong to feed the 1837-keV level, and absence of the above γ ray in the high-energy 1213- and 1898-keV coincidence spectra precludes the γ ray populating levels between 1850 and 2800 keV. The logft of 8.2 permits any spin between 0 and 4.

2622.8 ± 0.4-keV level. The energy of this level was determined by a weighted average of the 2623-keV γ ray and the cascade energy through the 882-keV level. A logf_1t of 7.5 limits the spin to 1, 2, or 3, and the presence of the 2623-keV transition to the ground state favors 1 or 2.

2699.9 ± 0.4-keV level. The energy of this level was determined from a weighted average of cascade energies through the 882-, 1898-, 2095-, and 2345-keV levels. A logf_1t of 6.8 limits the spin to

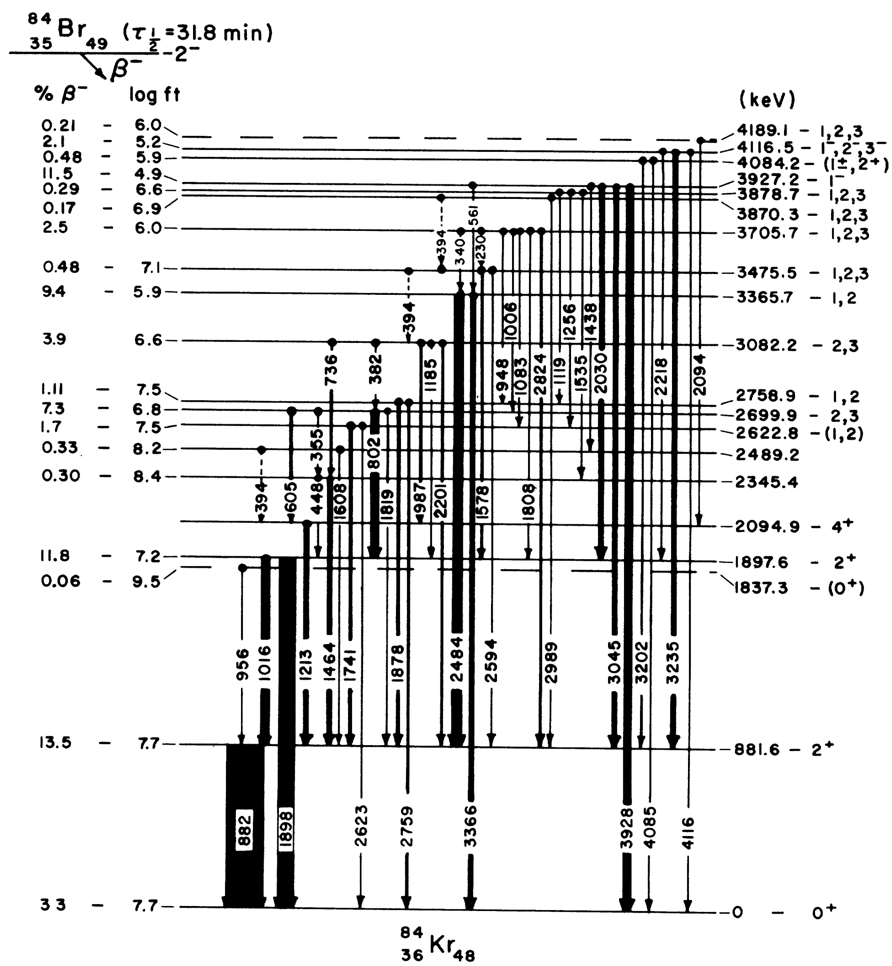

FIG. 6. Decay scheme of ^{84}Br from the present studies.

1, 2, or 3, but the strong 605-keV γ ray going to the 4^+ 2095-keV level eliminates 1. This result is consistent with an assigment of 3^- for the level determined from angular distributions in the (p, t) reaction.[7]

2758.9 ± 0.4-keV level. The energy was determined from a weighted average of the energies of the ground-state transition and the 1878 + 882-keV cascade. A $\log f_1 t$ of 7.5 limits the spin to 1, 2, or 3, and the relatively strong ground-state transition eliminates 3. A doublet of levels at 2758 and 2768 keV was observed in the (p, t) reaction.[7] The doublet was shown by angular distributions[7] to be a mixture of 2^+ and 5^- states. Our work demonstrates that the 5^- level must be at 2768 keV. The 5^- level was also observed by HASM to be populated by β^- decay from the high-spin isomeric state of ^{84}Br.

3082.2 ± 0.4-keV level. The level energy was determined from a weighted average of cascade energies through the 882-, 1898-, 2095-, 2345-, and 2700-keV levels. A $\log f_1 t$ of 6.5 limits the spin of the level to 1, 2, or 3, but the relatively high intensity of the 987-keV transition feeding the 4^+ level at 2095 keV eliminates 1. This level was given an assignment of 3^- by Levine and May on the basis of angular distributions from the (p, t) reaction.[7]

3365.7 ± 0.3-keV level. The energy of this level was determined from a weighted average of the energies of the ground-state transition and the 2484 + 882-keV cascade. This strongly populated level has a $\log f_1 t$ of 5.6 which limits its spin to 1, 2, or 3. The ground-state transition eliminates 3.

3475.5 ± 0.4-keV level. The energy of this level was determined from a weighted average of cascade energies through the 882- and 1898-keV levels. A $\log f_1 t$ of 6.7 limits the spin to 1, 2, or 3. This is contrary to the assignment of a spin of 4 by HASM.

3705.7 ± 0.4-keV level. This level energy was obtained from a weighted average of cascade energies through the 3476-, 3366-, 2759-, 2700-, 2623-, 1898-, and 882-keV levels. A $\log f_1 t$ of 5.5 limits the spin to 1, 2, or 3.

3870.3 ± 0.7-keV level. We postulate this new level on the basis of the coincidence of the 2989-keV γ ray with the 882-keV transition. The level energy was determined from the sum of the energies of the 2989- and 882-keV γ rays. A $\log f_1 t$ of 6.3 limits the spin to 1, 2, or 3.

3878.7 ± 0.8-keV level. This new level was postulated from the presence of the 1119- and 1256-keV γ rays in the high-energy coincidence spectrum and the 1535-keV γ ray in the 1464-keV coincidence spectrum. The presence of the 1119-keV γ ray in the 1898-keV coincidence spectrum is due to its coincidence with the 1878-keV transi-

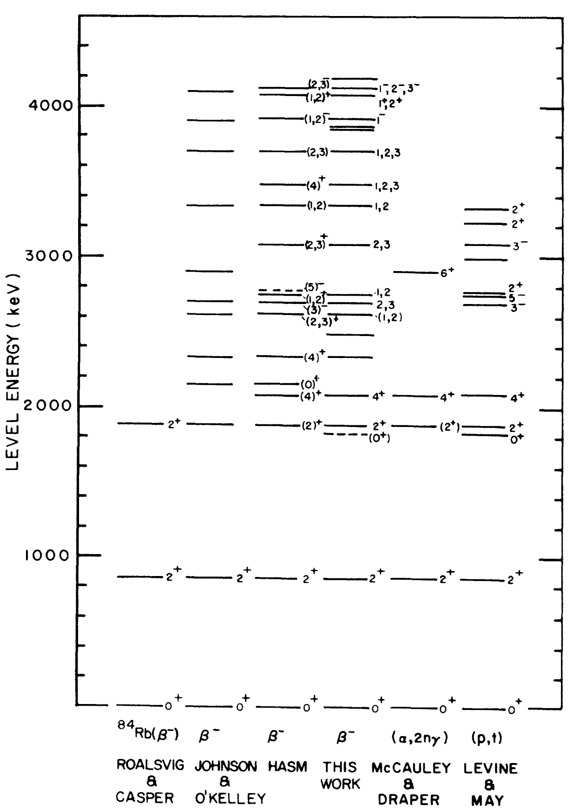

FIG. 7. Comparison of our ^{84}Kr level scheme with the results of decay and reaction studies.

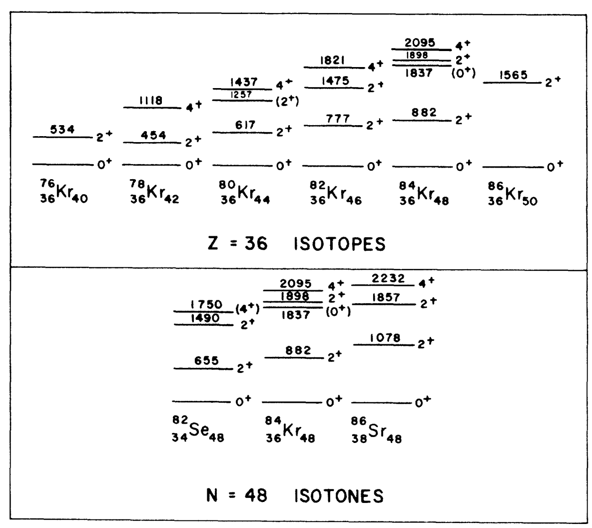

FIG. 8. Systematics of one- and two-phonon levels for nuclei with $Z = 36$ and with $N = 48$. All energies are in keV. Levels for the $Z = 36$ nuclei are from Ref. 6. Levels for the $N = 48$ nuclei were obtained from C. M. Lederer, J. M. Hollander, and I. Perlman, *Table of Isotopes* (Wiley, New York, 1967).

tion. The level energy was determined from a weighted average of cascade energies through the 2345-, 2623-, and 2759-keV levels. A $\log f_1 t$ of 6.0 limits the spin to 1, 2, or 3.

3927.2 ± 0.4-keV level. The energy of this level was determined from a weighted average of cascade energies through the 882-, 1898-, 2489-, and 3366-keV levels and the energy of the ground-state transition. This level is fed by 11.5% of the total β strength and its low $\log ft$ of 4.9 implies that the level must have negative parity and a spin of 1, 2, or 3. The strongest depopulating transition is the one to the 0^+ ground state; thus a spin of 3 is ruled out and an $M2$ transition from a 2^- state appears unlikely. We thus give the level an assignment of 1^-.

4084.2 ± 0.7-keV level. This level energy was obtained from a weighted average of the energy of the ground-state transition and the 3202 + 882-keV cascade. A $\log f_1 t$ of 5.2 limits the spin to 1, 2, or 3, and the approximate equality of the intensity of the γ rays to the 0^+ ground state and 2^+ first-excited state favors $1^{\pm}$ or 2^+ for the level assignment.

4116.5 ± 0.7-keV level. This level energy was determined from a weighted average of the ground-state transition energy and cascade energies through the 882- and 1898-keV levels. The weak 4116-keV γ ray could be interpreted as a sum peak but a rough calculation gave a sum intensity weaker by a factor 6 than the observed intensity. A low $\log ft$ of 5.2 implies that the level is fed by an allowed β transition and has a negative parity. The spin of 1, 2, or 3 is possible from the $\log ft$. The weakness of the 4116-keV transition does not allow us to further limit the spin of the level.

4189.1 ± 0.6-keV level. This level energy was determined from the sum of the energies of the 2095-keV level and the 2094-keV γ ray. The existence of this level is based on the presence of the 2094-keV γ ray in the 1213-keV coincidence spectrum. The 2094-keV γ ray was demonstrated not to be due to summing by observing its intensity as a function of source-to-detector distance. Also, if the 4^+ assignment for the 2095-keV level is correct, decay directly to the ground state is highly improbable, and a ground-state transition from the 2095-keV level would not appear in the 882- and 1213-keV coincidence spectra. The $\log f_1 t$ of 5.1 limits the spin to 1, 2, or 3.

IV. CONCLUSION

The level scheme of ^{84}Kr determined by us is compared with decay[1-4] and reaction studies[6-7] in Fig. 7. Our γ-ray energies and intensities are generally in good agreement with those of HASM, but we have postulated new levels at 1837, 2489, 3870, 3879, and 4189 keV and placed 19 additional γ rays in the level scheme.

Low-lying states of even-even nuclei have been described by Kisslinger and Sorensen[11] in terms of simple quadrupole vibrations. The first excited 2^+ level represents the one-phonon state, while the two-phonon state at double the energy of the one-phonon state is a triplet with 0^+, 2^+, and 4^+ levels. In only a few cases have all three members of the triplet been observed. Systematics for one- and two-phonon states of nuclei with $Z = 36$ and nuclei with $N = 48$ are given in Fig. 8. The increase in energy of the first excited 2^+ state as closed shells are approached is obvious. A similar pattern for the two-phonon states is evident.

We observed all three members of the two-phonon triplet confirming the existence of the 0^+ member first seen by Levine and May[7] in the (p, t) reaction. The 4^+ member had been observed by HASM in decay studies, and its spin was determined by McCauley and Draper[6] from the $(\alpha, 2n\gamma)$ reaction. The simple vibrational model predicts the ratio between the energies of the two- and one-phonon state members to be two. Experimental values for this ratio in a wide variety of nuclei fluctuate somewhat,[12] but the average is about 2.2. In ^{84}Kr we obtain values of 2.08, 2.15, and 2.38 for the above ratio for the 0^+, 2^+, and 4^+ levels, respectively. The value of 2.38 for the 4^+ level is slightly higher than 2.0, but well below the rotational-model prediction of 3.33.

The vibrational model predicts the stopover transition from the 2^+ member of the triplet to the one-phonon state to be pure $E2$ and the crossover transition to the ground state to be strongly inhibited. The $M1$ contribution to the stopover transition has been measured[1] to be less than 1%, and our intensities indicate the ratio of the crossover to the stopover transition to be only 2.4 compared to a single-particle estimate of 46.

The vibrational model predicts a three-phonon state with an energy 3 times that of the one-phonon state. This state is a quintet with 0^+, 2^+, 3^+, 4^+, and 6^+ members, and would preferentially populate[12] two-phonon states over the one-phonon or ground states. In the region between 2400 and 3100 keV no good candidate for such a state is evident. The levels at 2700 and 3082 keV populate the two-phonon triplet, but have been shown by LeVine and May[7] to be 3^-. They probably correspond to octupole vibrations. The $\log ft$'s for β decay to the above 3^- states are 6.8 and 6.6, respectively. These decays are hindered in comparison to normal allowed decays in this region which are typically between 5 and 6. Similar hindered β transitions[12] between 2^--parent levels and the 3^--octupole state have been observed in ^{72}As, ^{88}Rb, and ^{92}Y. The logft's are 6.2, 6.7, and 7.1, respectively.

The level at 3927 keV, which was given an assignment of 1^- by us, is interesting, since the β strength populating it is rather large, 11.5% of the total, even though the level energy is rather high. Properties of the levels in ^{84}Kr below the 2200 keV seem to fit the simple vibrational picture quite well, and two octupole vibrational states have probably been observed above 2600 keV. A detailed quasiparticle calculation is needed in order to understand the structure of most of the states above 2200 keV.

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