Level properties of $^{85}_{37}Rb_{48}$ from the decay of the ^{85}Kr and ^{85}Sr isomers and the cluster-vibration model

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We have investigated the decay of $^{85}Kr^m$, $^{85}Kr^g$, $^{85}Sr^m$, and $^{85}Sr^g$ using Ge(Li) spectroscopy and intrinsic Ge Compton-suppression spectroscopy techniques. We observe levels at (J^π in parentheses) g.s. ($5/2^-$), 151.18 ($3/2^-$), 281.01 ($1/2^-$), 513.998 ($9/2^+$), 731.79 ($3/2^-$), 868.05 ($7/2^-$), and 921 ($1/2^-$,$3/2^-$) keV. Our data suggest that the ~880 keV level observed in (t,α) and (^{3}He,d) reactions is the known 868-keV level. The Q_{EC} value for the $^{85}Sr^m$ decay is calculated to be 1323±20 keV from our EC/β^+ intensity data. We use the cluster-vibration model to calculate the ^{85}Rb level structure and electromagnetic decay properties. For the latter, we discuss the role of the $M1$ tensor operator.

NUCLEAR STRUCTURE Cluster-vibration model, influence of $M1$ tensor term.

RADIOACTIVITY ^{85}Kr, ^{85}Kr^m, ^{85}Sr, and ^{85}Sr^m. Measured E_β,I_β. ^{85}Rb deduced levels, E_β, I_β, J, π. Ge(Li) detector, Compton-suppression spectrometer.

I. INTRODUCTION

A major problem in predicting the level structure of odd-mass spherical nuclei is the inability of the simple single-particle shell model to account for the large number of experimentally observed levels below the pairing gap.[1,2] Some of the "extra" levels in odd-mass nuclei have been accounted for in a phenomenological way by using a weak coupling model.[3-5] Recently, some success has been achieved in accounting for all the levels and their properties by incorporating explicit multiparticle excitations and their interaction with the vibrational field.[6-17] The odd-mass Rb nuclei with $Z = 37$ provide a test of these calculations for, as shown in Fig. 1, their level density below 800 keV changes drastically as the number of neutron pairs are changed.[18-40] Here we present our experimental studies which were aimed at clarifying the number and decay properties of the ^{85}Rb levels below 1 MeV. We then compare the results of cluster-vibration model calculations with the ^{85}Rb levels and their properties. Finally, we discuss the role of the tensor term in l-forbidden $M1$ transitions.

Since the last published compilation on A = 85 nuclei by Horen,[28] several studies of ^{85}Rb have been reported. The levels of ^{85}Rb have been studied by (^{3}He, d), (Ref. 29), (t, α) (Ref. 24) and (d, ^{3}He) (Ref. 31) reactions, Coulomb-excitation,[26] (n, $n'\gamma$) reactions,[23,25] and decay studies,[18-21] including our initial reports.[28,30] A number of the levels observed in reaction spectroscopy have l-value assignments inconsistent with the decay properties observed in the two (n, $n'\gamma$) studies. In addition, a level of approximately 880 keV has been reported in some transfer reaction studies but not in all the related studies.

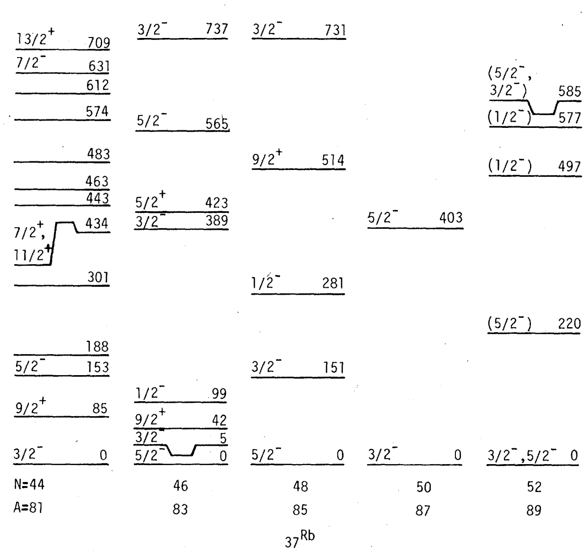


FIG. 1. Experimentally observed levels of odd-mass Rb nuclei below 800 keV. These levels have been taken from the data presented in Refs. 18 to 44, inclusive.

II. EXPERIMENTAL

Using gas-chromatography techniques, we prepared sources of 10.37-y $^{85}Kr^{g}$ from the gross fission products of an underground nuclear detonation.[41,42] A commercially available source was also used. Approximately 1 Ci of $^{85}Kr^{g}$ was adsorbed onto 1 g of charcoal and sealed in a quartz counting ampule.

Two types of 4.48-h $^{85}Kr^{m}$ sources were made. The first source was mass separated after gas-chromatographic separation of krypton from gross fission products.[41,42] Since this source was too weak, a second source was prepared from gaseous fission products but was not mass separated in order to achieve reasonable counting statistics.

The $^{85}Kr^{g}$ was counted several times using two different Compton-suppression spectrometers: one with a Ge(Li) detector,[43] the other with an intrinsic-Ge detector.[44] The $^{85}Kr^{m}$ spectra were taken with an LEPS, a large-volume Ge(Li) detector, and Compton-suppression spectrometers. In addition, the sources were counted simultaneously with known energy standards.[45,46] All spectra in this study were analyzed on CDC-7600 computers using the GAMANAL code developed by Gunnink and Niday.[47]

Sources of 69.5-min $^{85}Sr^{m}$ were produced by irradiating enriched ^{84}Sr in the Livermore Pool-Type Reactor (LPTR). Since the initial experiments showed the presence of major non-Sr contaminants, the enriched ^{84}Sr was chemically purified by adsorbing Sr ions out of an aqueous solution of $^{84}Sr(NO_3)_2$ on a Dowex-50 cation column. Any impurities adsorbed on the column were stripped off with 0.5 M α-hydroxy isobutyric acid (α-HIBA) with pH 5.2. The Sr was eluted with 1 M α-HIBA at pH 5.2 and precipitated as $SrCO_3$ using NH_3 and CO_2. The $SrCO_3$ was washed, dried, weighed, divided into several vials, and sealed for irradiation. Upon completion of irradiation, the $SrCO_3$ was removed from the irradiation vial and sealed in a counting planchette. A new source was produced every 60 minutes, and during each 60-min period spectra were taken sequentially on four separate Ge(Li) spectrometers. Each spectrometer accumulated data for approximately 500 min.

Sources of 65.19-d $^{85}Sr^{g}$ were produced by the $^{85}Rb(\alpha,4n)^{85}Y^{m+g} \rightarrow {}^{85}Sr^{g}$ sequence using enriched ^{85}Rb targets at the Lawrence Berkeley Laboratory (LBL) 223-cm cyclotron. The $^{85}Sr^{g}$ sources were chemically purified by the same technique as above to eliminate any possible contaminants. Again, singles, Compton-suppression, and energy-calibration spectra were taken.

III. RESULTS AND DECAY SCHEMES

A. $^{85}Kr^{m}$ decay

In Table I we present the energies and intensities of the γ rays we assign to the decay of $^{85}Kr^{m}$. A portion of the Ge(Li)-LEPS spectra showing the 129- and 151-keV γ rays is given in Fig. 2. The decay scheme deduced from our data is shown in Fig. 3(a). The log*ft* values were calculated using a Q_β of 991 ± 2 keV and a half-life of 4.475 ± 0.010 hr as reported by Wohn *et al.*[20]

We observe population of the 732-keV level observed in Coulomb excitation.[26] Bond and Kumbartski[26] have shown that the J^π value for this level is $\frac{3}{2}^-$; thus, the implied β transition from $^{85}Kr^{m}(\frac{1}{2}^-)$ is *allowed*. We also observe population of the 732-keV level in the decay of $^{85}Sr^{m}$ (see Sec. III C).

B. $^{85}Kr^{g}$ decay

The energies and intensities of the γ rays from the decay of $^{85}Kr^{g}$ are listed in Table II. The $^{85}Kr^{g}$ decay scheme is shown in Fig. 3(b). The Compton-suppression spectra of the decay of $^{85}Kr^{g}$ and details of the 151-, 362-, and 514-keV peaks from the intrinsic-Ge Compton-suppression spectrometer are shown in Figs. 4(a)–4(d). From our limit on the intensity of any 129-keV γ ray, obtained with the Compton-suppression system, we calculate a lower limit of 17 for the log*ft* value for the unique third-forbidden β decay from $^{85}Kr^{g}$ to the 281-keV level. We have observed for the first time the $E3$ transition from the 514-keV $\frac{9}{2}^+$ level to the 151-keV $\frac{3}{2}^-$ level in ^{85}Rb. Our branching ratio of five 362-keV γ rays per 10^6 decays of the 514-keV level ($T_{1/2}$ = 1 μs) gives an $E3$ hindrance of 75 relative to the Moszkowski estimate.[48] This value is quite different from the enhancement of 3 spu for similar transitions in the indium nuclei.[49,50] More data of a systematic nature are needed before the role of the octupole vibration in these types of transitions can be discussed.

TABLE I. γ rays from the decay of $^{85}Kr^{m}$.

$E_\gamma(\Delta E_\gamma)$ (keV)	$I_\gamma(\Delta I_\gamma)$ (relative)	Assignment From	To
129.81 (2)	4.0 (1)	281	151
151.19 (3)	1000 (5) [a]	151	GS
281.01 (4)	≤0.01	281	GS
304.87 (2)	187 (2)	I.T.	
451.0 (1)	0.15 (5)	732	281
580.6 (1)	≤0.01	732	151
731.6 (3)	0.10 (4)	732	g.s.

[a] Fiducial value. The error represents statistical and fitting error only.

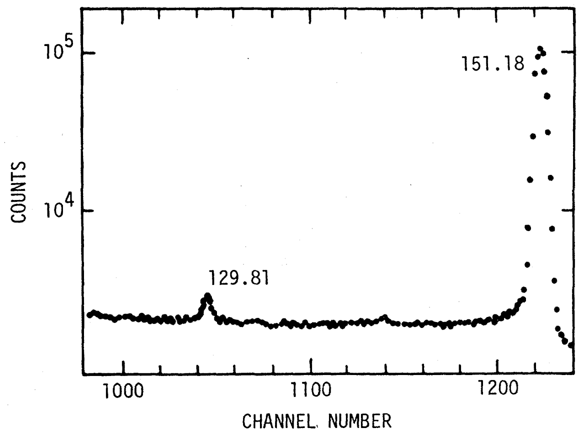


FIG. 2. Portion of γ-ray spectrum from the decay of $^{85}Kr^m$ showing the 129- and 151-keV γ rays. (N.B.: small peak at channel 1140 is the 151-keV Ge escape peak.)

C. $^{85}Sr^m$ decay

In Figs. 5(a) and 5(b) we show the $^{85}Sr^m$ spectra. In Table III we present the γ-ray intensities for the decay of $^{85}Sr^m$. In Fig. 6 we show the decay scheme of $^{85}Sr^m$. If we use our values for the positron intensity and E.C. feeding of the 151-keV level, we obtain an EC/β^+ ratio of $(1.9 \pm 0.3) \times 10^3$. This corresponds to a Q value of 1323 ± 20 keV for the decay of the isomer.[34] Previously, only an estimated Q value of 1308 keV was available.[28]

D. $^{85}Sr^g$ decay

The γ-ray energies and intensities for the decay of $^{85}Sr^g$ are given in Table IV, and Fig. 7 shows the $^{85}Sr^g$ decay scheme. The observation of the 951-keV γ ray was not unambiguous; therefore, we report an upper limit for its intensity and do not include it in our decay scheme.

Bubb *et al.*[21] have stated that the decay of $^{85}Sr^g$ populates only the $\frac{9}{2}^+$ level at 514 keV in ^{85}Rb. They did not observe γ rays at 880 and 356 keV, which were previously reported[22,23] and assumed to deexcite a level at approximately 880 keV. They further claimed that the $^{85}Sr^m$ decay populates only the 151-keV $\frac{3}{2}^-$ level in ^{85}Rb. Our results, as shown in Table V and Fig. 7, disagree with those of Bubb *et al.*[21] We do observe 868-, 716-, and 354-keV γ rays that deexcite a level at 868 keV.[18] This level has been observed in recent Coulomb-excitation and $(n, n'\gamma)$ experiments.[25,26,32] We note that Vatai *et al.*[19] found tentative evidence for 868-keV γ rays; however, they did not have enough sensitivity in their measurement to observe the 716- or 354-keV γ rays and hence definitely establish a level.

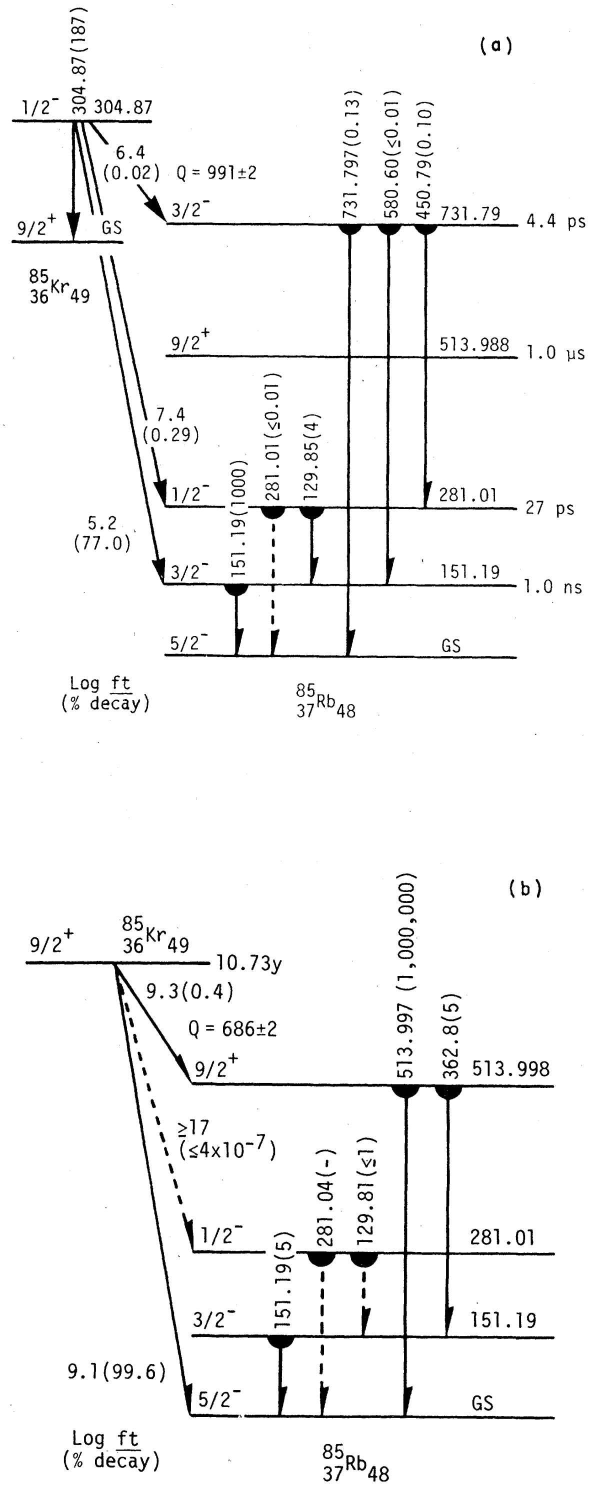


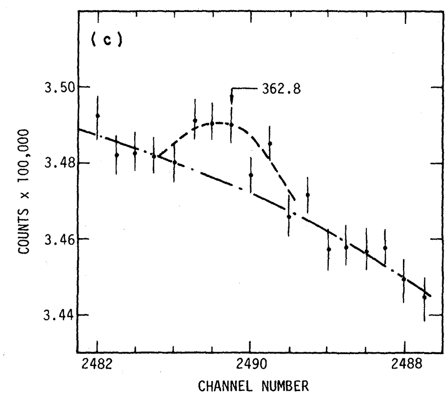
FIG. 3. (a) Decay scheme for $^{85}Kr^m$. (b) Decay scheme for $^{85}Kr^g$. The 281-keV γ ray is not observed in either of these decays; however, it is observed in the decay of $^{85}Sr^m$ with a branching ratio of 2.7×10^{-3} (see Fig. 6).

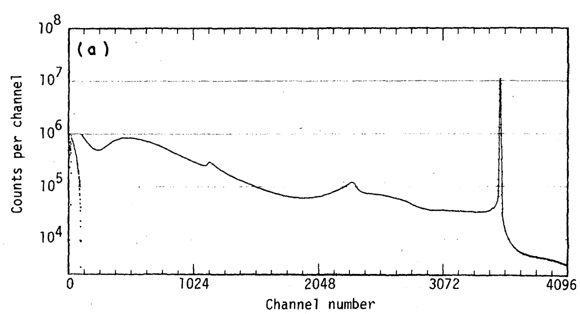
TABLE II. γ rays from the decay of $^{85}Kr^g$.

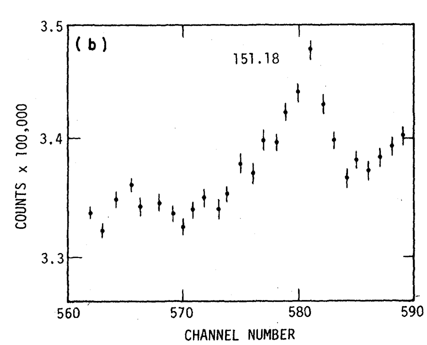
$E_\gamma(\Delta E_\gamma)$ (keV)	$I_\gamma(\Delta I_\gamma)$ (relative)	Assignment From	To
129.81 (2)	≤ 1	281	151
151.18 (3)	5 (3)	151	GS
362.81 (4)	5 (1)	513	151
513.997 (5)	10^6	513	GS

E. ^{85}Rb level assignments

In Table V we present a compendium of the ^{85}Rb levels observed in the various studies. The 868- and 919-keV levels have been observed in several studies[25,26,32] while a level at approximately 880 keV has been suggested.[24,29] Our work supports the levels at 868 and 919 keV but we obtain no evidence for a level at 880 keV. The 868-keV level has been observed in Coulomb-excitation studies[26] as well as in $(d, {}^3\text{He})$ (Ref. 31) and $(n, n'\gamma)$ studies.[25,32] The 919.7-keV level is observed in both $(n, n'\gamma)$ studies[25,32] and is reported to have an $l=3$ value in $(d, {}^3\text{He})$ studies[31] and an $l=1$ value in (t, α) studies.[24] None of the decay, Coulomb excitation,[26] $(d, {}^3\text{He})$, (Ref. 31) or $(n, n'\gamma)$ studies[25,32] report a level at approximately 880 keV. However, both (t, α) (Ref. 24) and $({}^3\text{He}, d)$ (Ref. 29) studies report a single peak at about 880 keV. Presumably this 880-keV peak is due to the 868-keV level, the energy discrepancy being due to the rather poor energy resolution of the charged-particle spectrometers. Our $^{85}Sr^g$ decay data imply a J^π of $\frac{7}{2}^-$ for the 868-keV level, in contrast to the $(\frac{1}{2}^-, \frac{3}{2}^-)$ assignment suggested by the charged-particle reaction experiments.[24,29,31] In the case of the 919-keV level, the possible β-decay feeding from $^{85}Sr^m$ $(\frac{1}{2}^-)$ and the $l=1$ (t, α) result suggest a







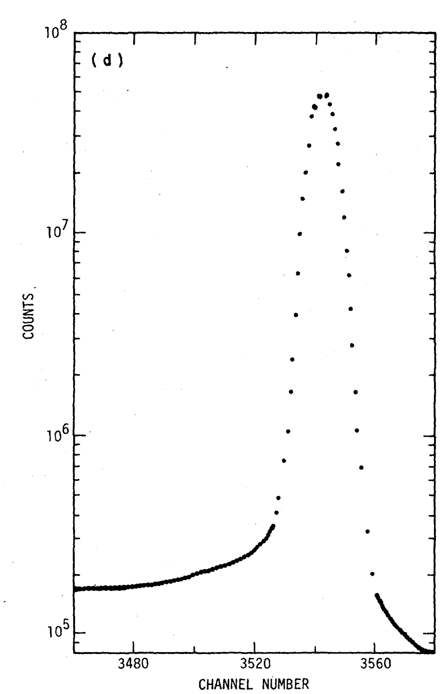


FIG. 4. (a) Early spectra of the $^{85}Kr^g$ decay taken with an intrinsic Ge Compton-suppression spectrometer (CSS). Large hump at low energy is bremsstrahlung from the intense β branch. (b) Detail from CSS showing 151.18-keV γ ray. (c) Detail from CSS showing 362.8-keV γ rays. (d) Detail from CSS showing the shape and statistics of 514-keV γ ray. The duration of count for Fig. 1(a) is approximately one week, while here (b) and (c) are from a 30-day counting period; the values given in Table II are average values of five long-duration Compton-suppression measurements.

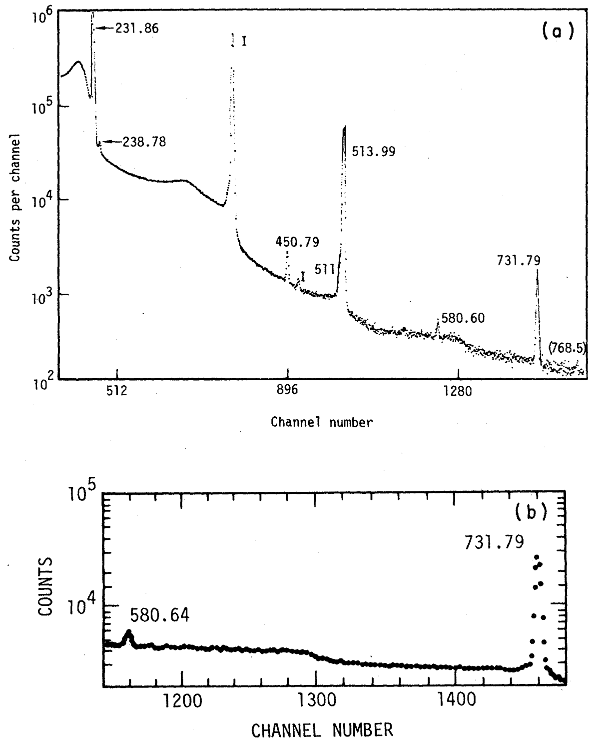


FIG. 5. (a) $^{86}Sr^m$ Ge(Li) spectrum accumulated with a graded absorber between source and detector during the second half-life period. The peaks labeled I are the impurity lines from the decay of $^{87}Sr^m$; (b) $^{85}Sr^m$ spectra taken with Pb-Cd absorbers in front of a large-volume Ge(Li) detector during first half-life period.

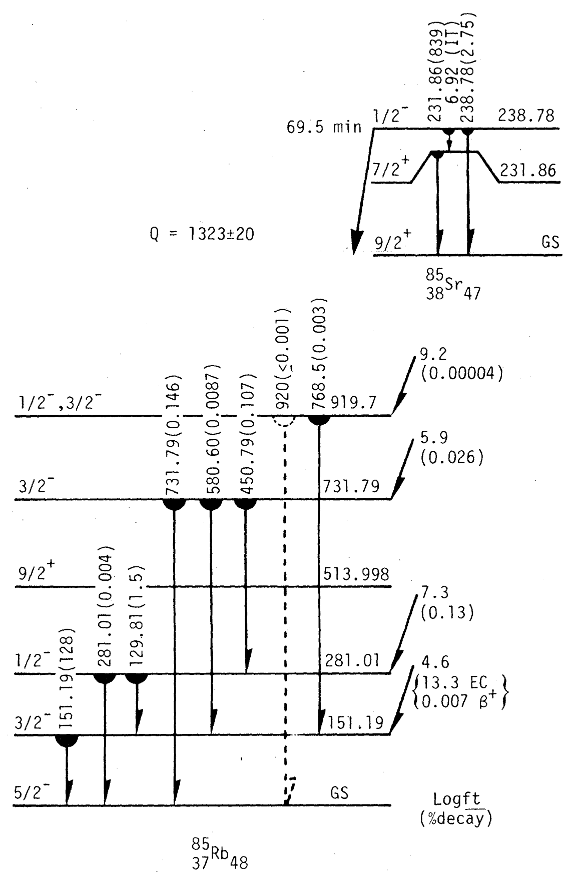


FIG. 6. Decay scheme of $^{85}Sr^m$.

$\frac{1}{2}^-$ or $\frac{3}{2}^-$ assignment.

A unique J^π assignment for the 951.2-keV level cannot be made on the basis of the available evidence. The (t,α) study gives $l=3$ or 4, the $(d,{}^3He)$ an $l=1$ value, and the $({}^3He,d)$ an $l=2$ value. The two $(n,n'\gamma)$ studies each give somewhat different information. In the $(n,n'\gamma)$ studies of Torti *et al.*,[25] enriched ^{85}Rb targets were used and only two transitions out of this level were observed, of energy 951.3 and 800.2 keV. Barnard

TABLE III. γ rays from the decay of $^{85}Sr^m$.

$E_\gamma(\Delta E_\gamma)$ (keV)	$I_\gamma(\Delta I_\gamma)$ (per 1000 decays)	Assignment From	To
129.815 (35)	1.5 (4)	281	151
151.194 (15)	128 (3)	151	GS
231.860 (20) [a]	839 (16)		
238.78 (5) [a]	2.75 (5)		
281.01 (3)	0.004 (2)	281	GS
450.79 (5)	0.107 (5)	731	281
511.00 (–) [b]	0.14 (2)		
580.64 (5)	0.0087 (9)	732	281
731.797 (15)	0.146 (8)	732	281
768.5 (10) [c]	0.0030 (25)	922	151
[919.8 (9)] [c,d]	0.0010 (5)	919	g.s.

[a] Transition occurs in the parent nucleus.
[b] Annihilation radiation.
[c] Measured from first half-life data.
[d] Evidence for this γ ray is tentative.

TABLE IV. γ rays from the decay of $^{85}Sr^g$.

γ-ray energy (ΔE) (keV)	Relative intensity (ΔI)	Assignment From	To
129.80 (5)	≤0.005	281	151
151.18 (3)	0.012 (9)	151	GS
513.997 (2)	997.0 [a]	514	GS
354.06 (5)	0.005 (2)	868	514
362.82	≤0.01	514	151
716.87 (5)	0.0032 (3)	868	151
868.05 (5)	0.125 (5)	868	g.s.
(951.0 (5)) [b]	(≤0.0003) [b]	(951)	(g.s.)

[a] Total transition intensity taken as 1000.
[b] A γ ray of 951 keV was observed in two spectra taken with high counting statistics. However, the evidence for its assignment to ^{85}Sr decay is tentative.

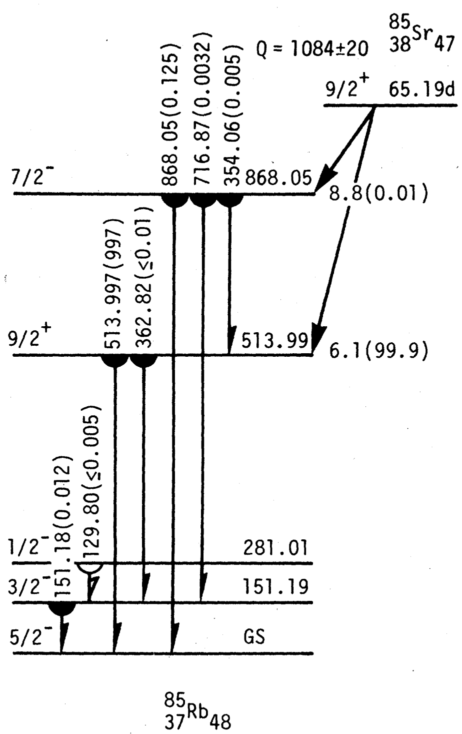


FIG. 7. Decay scheme of $^{85}Sr^{g}$. Although unmeasured and not shown in this figure, it should be noted that the possibility of unique first-forbidden (u1f) beta decay exists between the $J^{\pi}=\frac{9}{2}^{+}$ $^{85}Sr^{g}$ and the $J^{\pi}=\frac{5}{2}^{-}$ ground state of ^{85}Rb. A $\log f_1 t$ value of 9.7 is consistent with u1f beta decay in this mass region (e.g., ^{84}Rb has a 9.6 and ^{86}Rb has a 9.8 $\log f_1 t$ value). Using this value, the half-life and measured Q value, the branching ratio to the ground state, would be one percent.

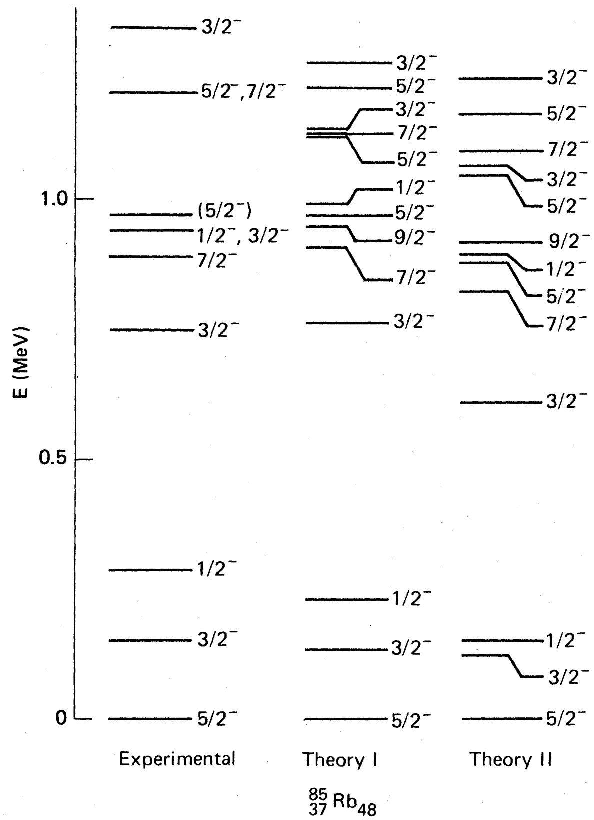


FIG. 8. Comparison of the experimental negative-parity levels of ^{85}Rb and the theoretical levels calculated in the cluster-vibration model (see text for a description of parametrization I and II).

TABLE V. Comparison of experimental results from ^{85}Rb level studies.

Level energy (keV)	J	Log ft Parent J: Kr $\frac{1}{2}^-$	Sr $\frac{1}{2}^-$	Sr $\frac{9}{2}^+$	Kr $\frac{9}{2}^+$	l[a] p (t,α)	l[b] p $(d,{}^3He)$	l[c] p $({}^3He,d)$	$(n,n'\gamma)$ Ref. d	Ref. e
0.0	$\frac{5}{2}^-$				9.1	3	3	3		
151.19	$\frac{3}{2}^-$	5.2	4.6			1	1	1	151.2	151.2
280.01	$\frac{1}{2}^-$	7.4	7.3		6.3	1	1	1	281.0	281.0
513.998	$\frac{9}{2}^+$			6.1	9.3	4	4	4	514.0	514.0
731.79	$\frac{3}{2}^-$	6.4	5.9			(3, 4)	1	1	731.9	732.0
868.05	$\frac{7}{2}^-$			8.8		1[f]	1	1[g]	868.7	868.5
919.7	$(\frac{1}{2}^-,\frac{3}{2}^-)$		≥9.2			1[h]	3		919.6	919.8
951.2	$(\frac{5}{2}^-)$			(?)		(3, 4)	1	2	951.3	951.1
1175.8	$\frac{5}{2}^-,\frac{7}{2}^-$					(4)	(3)	4	1176	1175.7

[a] See Ref. 24.
[b] See Ref. 31.
[c] See Ref. 29.
[d] See Ref. 32.
[e] See Ref. 25.
[f] Value for "880-keV" level.
[g] Value for "883-keV" level.
[h] Value for "925-keV" level.

TABLE VI. Wave functions of the low-lying negative-parity states. Only amplitudes larger than 4% are listed. The assignment of the total angular momentum is omitted from the basis vectors.

$\frac{5}{2}_1^-$		$\frac{7}{2}_1^-$	
$\|[(p_{1/2}^{-2})0,f_{5/2}^{-1}]\frac{5}{2},00\rangle$	−0.357	$\|[(p_{5/2}^{-2})0,f_{5/2}^{-1}]\frac{5}{2},12\rangle$	0.335
$\|[(p_{3/2}^{-2})0,f_{5/2}^{-1}]\frac{5}{2},00\rangle$	−0.483	$\|[(f_{5/2}^{-2})4,p_{1/2}^{-2}]\frac{7}{2},00\rangle$	−0.328
$\|(f_{5/2}^{-3})\frac{5}{2},00\rangle$	−0.628	$\|[(p_{3/2}^{-2})0,f_{5/2}^{-1}]\frac{5}{2},12\rangle$	0.386
$\frac{3}{2}_1^-$		$\|(f_{5/2}^{-3})\frac{5}{2},12\rangle$	0.565
$\|[(p_{1/2}^{-2})0,p_{3/2}^{-1}]\frac{3}{2},00\rangle$	−0.315	$\frac{1}{2}_2^-$	
$\|(p_{3/2}^{-3})\frac{3}{2},00\rangle$	−0.275	$\|[(p_{1/2}^{-2})0,f_{5/2}^{-1}]\frac{5}{2},12\rangle$	0.211
$\|[(f_{5/2}^{-2})0,p_{3/2}^{-1}]\frac{3}{2},00\rangle$	−0.719	$\|[(p_{1/2}^{-1}p_{3/2}^{-1})2,f_{5/2}^{-1}]\frac{5}{2},00\rangle$	−0.316
$\|[(f_{5/2}^{-2})0,p_{3/2}^{-1}]\frac{3}{2},12\rangle$	−0.209	$\|[(p_{3/2}^{-2})0,f_{5/2}^{-1}]\frac{5}{2},12\rangle$	0.392
$\frac{1}{2}_1^-$		$\|[(f_{5/2}^{-2})2,p_{3/2}^{-1}]\frac{1}{2},00\rangle$	0.268
$\|[(p_{3/2}^{-2})0,p_{1/2}^{-1}]\frac{1}{2},00\rangle$	−0.410	$\|[(f_{5/2}^{-2})0,p_{3/2}^{-1}]\frac{3}{2},12\rangle$	−0.448
$\|[(f_{5/2}^{-2})0,p_{1/2}^{-1}]\frac{1}{2},00\rangle$	−0.693	$\|(f_{5/2}^{-3})\frac{5}{2},12\rangle$	0.301
$\|[(f_{5/2}^{-2})0,p_{3/2}^{-1}]\frac{3}{2},12\rangle$	0.289	$\frac{5}{2}_2^-$	
$\|(f_{5/2}^{-3})\frac{5}{2},12\rangle$	0.292	$\|[(p_{1/2}^{-2})0,f_{5/2}^{-1}]\frac{5}{2},12\rangle$	−0.269
$\frac{3}{2}_2^-$		$\|[(f_{5/2}^{-2})2,p_{1/2}^{-1}]\frac{5}{2},00\rangle$	−0.260
$\|[(p_{1/2}^{-2})0,f_{5/2}^{-1}]\frac{5}{2},12\rangle$	−0.270	$\|[(f_{5/2}^{-2})0,p_{1/2}^{-1}]\frac{1}{2},12\rangle$	−0.430
$\|[(f_{5/2}^{-2})2,p_{1/2}^{-1}]\frac{3}{2},00\rangle$	0.310	$\|[(p_{3/2}^{-2})0,f_{5/2}^{-1}]\frac{5}{2},12\rangle$	−0.340
$\|[(p_{3/2}^{-2})0,f_{5/2}^{-1}]\frac{5}{2},12\rangle$	−0.293	$\|(f_{5/2}^{-3})\frac{5}{2},12\rangle$	−0.424
$\|(f_{5/2}^{-3})\frac{3}{2},00\rangle$	0.298		
$\|(f_{5/2}^{-3})\frac{5}{2},12\rangle$	−0.513		

et al.,[32] who used a natural Rb target (72.2% abundant in ^{85}Rb), report an additional 670.3-keV γ ray that decays to the $\frac{1}{2}^-$, 281-keV level with a 4% branching ratio, as well as a 438-keV transition to the $\frac{9}{2}^+$ 514-keV level with a 1% branching ratio. We note that the weak 438- and 670-keV γ rays could be masked in the study of Torti *et al.*[25] by the relatively high background. The observation of a transition to the 151-keV $\frac{3}{2}^-$ level does rule out the $l=4$ assignment. The possible β-decay feeding from ^{85}Sr^g ($J^\pi=\frac{9}{2}^+$) and the γ-ray branching observed in the $(n,n'\gamma)$ work of Bernard *et al.*[32] lead us to suggest a J^π value of $\frac{5}{2}^-$ for the 951-keV level.

IV. DISCUSSION

The 37 neutron nuclei have been treated by the cluster-vibration model (CVM).[51,52] Negative-parity states in ^{69}Ge and ^{67}Zn were described by coupling three holes in the subshell with single-particle configurations $p_{1/2}$, $p_{3/2}$, and $f_{5/2}$ to the quadrupole vibration; i.e., it was assumed that for these nuclei $N=40$ plays the role of a closed subshell. Here we extend this approach to $^{85}_{37}$Rb$_{38}$, which is a $Z=37$ nucleus. In the present calculation the following parametrization is used: The proton single-hole energies are $\epsilon(p_{1/2}^{-1})-\epsilon(f_{5/2}^{-1})=0.5$ MeV and $\epsilon(p_{3/2}^{-1})-\epsilon(f_{5/2}^{-1})=0.3$ MeV, the experimental energy of the first excited state in $^{88}_{40}$Zr$_{48}$ is taken as 1.06 MeV, the pairing strength is $G=0.4$ MeV, and the adopted value for the particle-vibration coupling strength is $a=0.3$ (parametrization I). The calculation is also performed for a slightly different parametrization, with $p_{1/2}^{-1}$ being lowered by 0.1 MeV and the parameter "a" being increased by 0.1 (parametrization II). The cluster-vibration Hamiltonian is diagonalized in the bases $|[(j_2j_2)J_{12},j_3]J,NR;I\rangle$. Here N represents the number and R the angular momentum of phonons, J is the angular momentum of the three-proton cluster, and I is the total angular momentum. Figure 8 shows the spectra calculated for parametrizations I and II, and Table VI presents the largest components ($\gtrsim$4%) in the wave functions of the low-lying states calculated in parametriza-

TABLE VII. Calculated $B(E2)$ and $B(M1)$ values for parametrizations I and II. For description see the text.

	I		II	
	$B(E2)$ (e^2b^2)	$B(M1)$ (μ_N^2)	$B(E2)$ (e^2b^2)	$B(M1)$ (μ_N^2)
$\frac{3}{2}^-_1 \to \frac{5}{2}^-_1$	0.0020	0.0220	0.0038	0.0226
$\frac{1}{2}^-_1 \to \frac{5}{2}^-_1$	0.0063		0.0061	
$\frac{1}{2}^-_1 \to \frac{3}{2}^-_1$	0.0066	1.0846	0.0072	1.0006
$\frac{3}{2}^-_2 \to \frac{5}{2}^-_1$	0.0138	0.0002	0.0156	0.0004
$\frac{3}{2}^-_2 \to \frac{3}{2}^-_1$	0.0008	0.0299	0.0023	0.0639
$\frac{3}{2}^-_2 \to \frac{1}{2}^-_2$	0.0011	0.0260	0.0018	0.0509
$\frac{7}{2}^-_1 \to \frac{5}{2}^-_1$	0.0115	0.0004	0.0136	0.0010
$\frac{7}{2}^-_1 \to \frac{3}{2}^-_1$	0.0001		0.0048	
$\frac{7}{2}_1 \to \frac{3}{2}^-_2$	0.0023		0.0126	
$\frac{1}{2}^-_2 \to \frac{5}{2}^-_1$	0.0049		0.0054	
$\frac{1}{2}^-_2 \to \frac{3}{2}^-_1$	0.0066	0.0743	0.0074	0.0550
$\frac{1}{2}^-_2 \to \frac{1}{2}^-_1$		0.0143		0.0137
$\frac{1}{2}^-_2 \to \frac{3}{2}^-_2$	0.0029	0.1228	0.0055	0.2242
$\frac{5}{2}^-_2 \to \frac{5}{2}^-_1$	0.0072	0.0009	0.0064	0.0025
$\frac{5}{2}^-_2 \to \frac{3}{2}^-_1$	0.0002	0.0001	0.0007	0.0002
$\frac{5}{2}^-_2 \to \frac{1}{2}^-_1$			0.0062	
$\frac{5}{2}^-_2 \to \frac{3}{2}^-_2$	0.0001	0.0001	0.00003	0.0017
$\frac{5}{2}^-_2 \to \frac{7}{2}^-_1$	0.0010	0.0121	0.0013	0.0504
$\frac{5}{2}^-_2 \to \frac{1}{2}^-_2$	0.0031		0.0066	

TABLE VIII. Comparison of the experimental and calculated electromagnetic properties of ^{85}Rb. Γ, $B(E2)$, Q (electric quadrupole moment), and μ (magnetic dipole moment) are expressed in units ps, e^2b^2, eb, and μ_N, respectively. The calculated transitions from each state are normalized to the corresponding experimental transition with strongest intensity (underlined values).

	I_γ Experiment	I_γ Theory (II)		I_γ Experiment	Theory (II)
			$\Gamma(\frac{3}{2}^-_1)$	1000	5000
			$\Gamma(\frac{1}{2}^-_1)$	27	18
$\frac{1}{2}^-_1 \to \frac{5}{2}^-_1$	0.004 (2)	0.005	$\Gamma(\frac{3}{2}^-_2)$	4	2
$\to \frac{3}{2}^-_1$	1.5 (4)	1.5	$\Gamma(\frac{7}{2}^-_1)$	4	8
$\frac{3}{2}^-_2 \to \frac{5}{2}^-_1$	0.10 (4)	0.08	$B(E2)$ $(\frac{3}{2}^-_1 \to \frac{5}{2}^-_1)$	0.0053 (6)	0.0038
$\to \frac{3}{2}^-_1$	0.01	0.4	$B(E2)$ $(\frac{1}{2}^-_1 \to \frac{5}{2}^-_1)$	0.0048 (6)	0.0061
$\to \frac{1}{2}^-_1$	0.15 (5)	0.15	$B(E2)$ $(\frac{3}{2}^-_2 \to \frac{5}{2}^-_1)$	0.0151 (5)	0.0156
$\frac{7}{2}^-_1 \to \frac{5}{2}^-_1$	0.125 (5)	0.125	$B(E2)$ $(\frac{7}{2}^-_1 \to \frac{5}{2}^-_1)$	0.027 (3)	0.0136
$\to \frac{3}{2}^-_1$	0.0032 (3)	0.004	$Q(\frac{5}{2}^-_1)$	+0.27	+0.10
			$\mu(\frac{5}{2}^-_1)$	+1.35	+1.26

tion II. These wave functions were used to calculate the electromagnetic properties. The effective charges and gyromagnetic ratios are as follows: $e^{\text{s.p.}}=1$, $e^{\text{VIB}}=3.5$, $g_R=Z/A$, $g_l=1$, $g_s=0.7\,g_s^{\text{free}}$, and $g_p=1.33$. The quenching of the g_s value was taken from Ref. 17 and the gyromagnetic ratio for the tensor $M1$ operator $(Y_2\times s)_1$ was taken in accordance with Refs. 53 and 54. The calculated $B(E2)$ and $B(M1)$ values for transitions between low-lying states are presented in Table VII, and a comparison of the experimental and calculated electromagnetic properties, branching ratios, half-lives, reduced transition probabilities, and static moments is given in Table VIII. The overall agreement between the experimental and calculated energy spectra and electromagnetic properties is reasonably good. However, the calculated branching ratio for the $\frac{3}{2}{}_2^-\to\frac{3}{2}{}_1^-$ transition is too large because $B(M1)$ $(\frac{3}{2}{}_2^-\to\frac{3}{2}{}_1^-)$ is not small enough. In fact, in the CVM, the $\frac{3}{2}{}_1^-\to\frac{3}{2}{}_1^-$ $M1$ transition is exactly forbidden in the zeroth-order approximation ($a=0$). However, in the present parametrization, which assumes an intermediate particle-vibration coupling strength, the $B(M1)$ $(\frac{3}{2}{}_2^-\to\frac{3}{2}{}_1^-)$ value is hindered only by two orders of magnitude. This value is rather sensitive to the parametrization used owing to the interference of many small partial contributions and therefore should not be interpreted too rigidly. In addition, in ${}^{85}_{37}\mathrm{Rb}_{48}$, the parametrization is adjusted to reproduce the experimental levels and such a treatment may not be the optimum one for the electromagnetic properties.

In the present calculation we also include the tensor term in the $M1$ operator. Generally, it drastically affects the $M1$ transitions, which are l-forbidden in zeroth order. In our case, such a transition is the $\frac{3}{2}{}_1^-\to\frac{5}{2}{}_1^-$ $M1$ transition, which is in zeroth order of the type $|[(f_{7/2}{}^{-2})0,p_{3/2}{}^{-1}]\frac{3}{2},00;\frac{3}{2}\rangle \to |[f_{7/2}{}^{-3})\frac{5}{2},00;\frac{5}{2}\rangle]$. In this case, the destructive interference between the higher-order contributions to the $M1$ transition moment for a standard

TABLE IX. Effect of the tensor term on $M1$ transitions.

Transition (From To)	Tensor term Without	With
	$B(M1)$ $(\mu_N{}^2)$	
l forbidden		
$\frac{3}{2}{}_1^-\to\frac{5}{2}{}_1^-$	0.000 03	0.023
Not l forbidden		
$\frac{1}{2}{}_1^-\to\frac{3}{2}{}_1^-$	1.100 7	1.000 6
$\frac{1}{2}{}_2^-\to\frac{3}{2}{}_1^-$	0.062 4	0.055 0
$\frac{3}{2}{}_2^-\to\frac{3}{2}{}_1^-$	0.063 9	0.063 9
$\frac{7}{2}{}_1^-\to\frac{5}{2}{}_1^-$	0.000 3	0.000 6

$M1$ operator is large, and such a transition is therefore strongly hindered in the presence of mixed wave functions.[54] Our calculated value for a standard $M1$ operator is $B(M1)$ $(\frac{3}{2}{}_1^-\to\frac{5}{2}{}_1^-)=0.000\,03$ μ_N^2; the calculated half-life of the $\frac{3}{2}{}_1^-$ state would then exceed the experimental value by three orders of magnitude, and the branching to the $\frac{5}{2}{}_1^-$ state would be too small by three orders of magnitude. However, inclusion of the tensor term in the $M1$ operator, with the usual value of the gyromagnetic ratio, $g_p=1.33$,[53,54] results in the calculated value $B(M1)$ $(\frac{3}{2}{}_1^-\to\frac{5}{2}{}_1^-)=0.023$ μ_N^2. This leads to a correct order of magnitude for the half-life $\tau(\frac{3}{2}{}_1^-)$. On the other hand, the other $M1$ transitions, which are not l-forbidden in zeroth order, are much less affected by the tensor $M1$ term. For comparison, we show in Table IX the calculated $B(M1)$ values for a standard $M1$ operator and those for the $M1$ operator with the tensor term included.

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