Cluster-vibrational-field model for ^{95}Mo and levels populated in the decay of $^{95}Tc^{m,g}$†

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The levels of ^{95}Mo populated in the decay of 20-h$^{95}Tc^{g}$ and 61-day$^{95}Tc^{m}$ decay have been studied using singles and Compton suppression Ge(Li) γ-ray spectrometers and a Si(Li) conversion electron spectrometer. We find 20 γ rays in the decay of $^{95}Tc^{g}$ and 26 γ rays in the decay of $^{95}Tc^{m}$. Using these data we identify 16 levels in ^{95}Mo and measure a total positron branch of (0.24 ± 0.03)% for the decay of $^{95}Tc^{m}$. A cluster-vibrational-field coupling model calculation has been performed for ^{95}Mo and rather good agreement is found between the model predictions and our experimentally observed level ordering and level decay branching ratios.

[RADIOACTIVITY $^{95}Tc^{g}$, $^{95}Tc^{m}$ [from Mo(p,xn), ^{93}Nb($\alpha,2n$)]; measured E_γ, I_γ, E_{ce^-}, I_{ce^-}, $T_{1/2}$; deduced logft. ^{95}Mo deduced levels, J,π, $B(M1)$, $B(E2)$ Ge(Li) Si(Li) detectors, enriched and natural targets.]

I. INTRODUCTION

An excess of levels beyond that expected from a simple single particle model has been identified from decay scheme and reaction spectroscopy studies of nuclides a few nucleons removed from closed shells.[1] This effect is particularly pronounced when nuclei with three particles beyond a shell closure are compared with nuclei with one particle beyond shell closure. The number and electromagnetic decay properties of the levels in the former led to the suggestion of particle clustering; for example, Alaga and co-workers have suggested that the clustering of nucleons and their interaction with the nuclear vibrational field could explain these phenomena.[2-4] One of the most demanding tests of any model is its ability to correctly replicate the experimental electromagnetic decay properties of nuclear levels. We have tested the cluster-vibration-field (CVF) model by undertaking systematic studies of nuclei with three protons (I with $Z=53$)[5-7] beyond shell closure and three proton holes (Ag with $Z=47$)[8-10] in the $Z=50$ shell. In these studies it was found that the CVF model duplicates the low energy levels and their properties fairly well. Our current studies of the $N=85$ nuclei[11-13] with three neutrons beyond the $N=82$ shell have demonstrated the usefulness of the CVF model in these nuclei as well. Unfortunately, few cases can be studied in sufficient detail to provide a critical test of the lighter neutron nuclei such as the $N=53$ nuclei. As shown in Fig. 1, the odd mass Mo($Z=42$) nuclei[14-18] exhibit the property of increased level density at low energies as three particles are added beyond shell closure. Experimentally ^{95}Mo is an ideal case since its gross level properties can be studied by transfer reactions and its detailed electromagnetic decay properties can be studied by both decay and in-beam techniques.[14] Unfortunately, to date no decay scheme spectroscopy technique has proved to be a sensitive enough probe to permit a comprehensive test of model calculations. Here we report our ability to probe the electromagnetic decay properties of ^{95}Mo levels populated in the decay of $^{95}Tc^{m}$ and $^{95}Tc^{g}$ by using Compton suppression and ancillary γ-ray and conversion electron spectrometers. Concomitantly we have extended the CVF model for ^{95}Mo and carried out a detailed comparison between experiment and theory.

Our original motivation for this work was to improve the accuracy of ^{95}Tc decay data in support of measurements of the rate of uptake of ^{95}Tc by *Haliotis cracherodii* and *Haliotis rufescens*.[19] Our experiments have resulted in the absolute γ-decay rate of ^{95}Tc and in the process we have accumulated significant new information about the decay schemes of $^{95}Tc^{g}$ and $^{95}Tc^{m}$ and the level decay properties of ^{95}Mo. Recent articles by Antoneva *et al.*,[20] Krämer and Huber,[21] Behar, Garber, and Grabowski,[22] Bindal, D. H. Youngblood, and R. L. Kozub,[23,24] and Hopke and Meyer[25] have dealt with the level scheme of ^{95}Mo as populated in radioactive decay. Other pertinent recent work in-

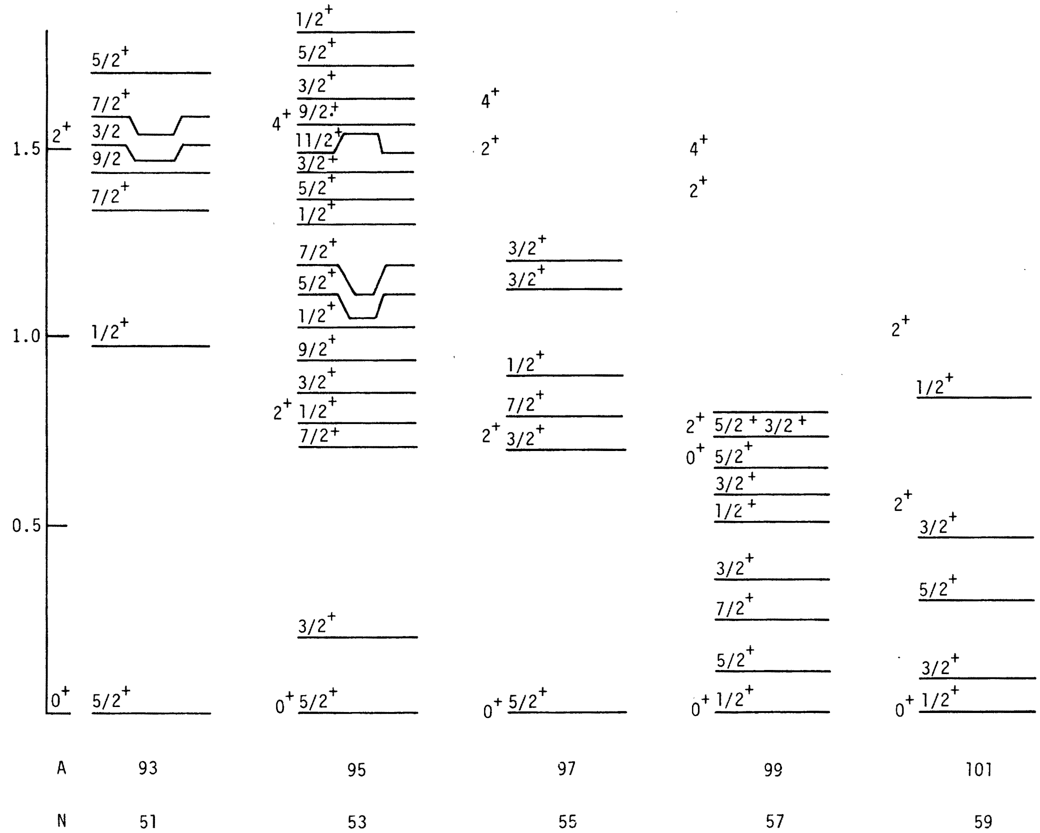

FIG. 1. Levels of odd mass Mo nuclei (taken from this work and Refs. 14–18).

cludes a Coulomb excitation study by Barrette *et al.*,[26] and Schoonover *et al.*,[27] who performed (^{3}He, α) reaction studies. Early work on ^{95}Mo has been well summarized by Medsker and Horen[14] where a complete bibliography can be found.

II. EXPERIMENTAL METHODS AND RESULTS

A. Source preparation

Radioactive sources of mixtures of ^{95}Tc^g and ^{95}Tc^m were obtained in three ways. The first method was to produce a mixed ^{95}Tc source by the (p, xn) reaction on very high purity Mo metal. Since natural Mo consists of seven stable isotopes ranging from ^{92}Mo to ^{100}Mo this method yielded a complex mixture of Tc activities. Although this source was not well suited for study of ^{95}Tc decay it was very useful for establishing a Tc-decay γ-ray catalog for comparison with sources produced by other reactions on materials whose chemical purity was less certain.

A second source was produced by the ^{93}Nb$(\alpha, 2n)$-^{95}Tc reaction at the Lawrence Berkeley Laboratory 224-cm cyclotron. This source was quite intense, ~100 mCi, and was used in connection with a Compton-suppression γ-ray spectrometer. A third source was obtained commercially from New England Nuclear Corp. This source, 30 mCi of ^{95}Tc^m, was chemically isolated from its decay products and electrodeposited on a thin Al support foil.

B. γ-ray and conversion electron measurements

We used a variety of detector systems to measure the γ-ray spectra from ^{95}Tc^g and ^{95}Tc^m. Initial counting of the cyclotron source was done for a 20-h period at constant counting rate on a Compton-suppression spectrometer using a 1.27-cm Pb absorber. This was followed by three 20-h counting periods without absorbers at constant geometry. After completion of the above data taking the Tc fraction was chemically separated from the cyclotron source and thin sources of Tc activity were electrodeposited on Al foils. These sources were counted using a planar Ge(Li) detector with a Be window to measure the low-energy γ-ray spectrum and large volume detectors (~50 cm^3) to obtain accurate γ-ray intensities over the range 0–2 MeV. Conversion electron spectra were taken with a Si(Li) spectrometer using the electroplated source.

TABLE I. γ rays assigned to ^{95}Tc^{g} decay.

$E_\gamma(\Delta E_\gamma)$	$I_\gamma(\Delta I_\gamma)$ [a]	Assignment
126.03(4)	0.11(1)	1552→1426
(126.97)	(<0.005)	(1074→948)
181.88(5)	0.027(8)	948→766
204.12(1)	3.3(4) [b]	204→0
307.93(2)	0.37(1)	1074→766
(467.10)	<0.001	(1541→1074)
478.00(50)	0.14(5)	1552→1074
(495.16)	<0.015	(1552→1057)
561.67(10)	0.15(6)	766→204
593.16(6)	0.23(7)	1541→948
604.04(2)	3.24(9)	1552→948
765.79(1)	1000(2)	766→0
774.99(1)	0.18(5)	1541→766
785.93(2)	1.55(9)	1552→766
869.60(3)	3.38(8)	1074→204
947.67(2)	20.8(2)	948→0
1056.70(25)	0.016(9)	1057→0
1073.71(2)	39.9(4)	1074→0
1221.90(15)	0.10(4)	1426→204
1441.00(90)	0.007(4)	(1645→204)
1551.71(5)	0.235(9)	1552→0
1645.00(90)	0.006(3)	(1645→0)
(1683)	0.0001	(1683→0)

[a] Normalized to 100 at 765.79 keV.
[b] Intensity component due to ^{95}Tc^{m} decay has been subtracted.

The commercial source of 61-day ^{95}Tc^{m} was counted using the Compton-suppression system for a variety of time intervals up to 40 days duration in order to identify very low intensity transitions associated with the 61-day half-life. Coincidence measurements were also made with the LLL mega-channel coincidence spectrometer.

Detector efficiency and energy calibrations were determined using primary standard sources.[28] Several secondary standards whose relative γ-ray intensities are well known were used to further define the response curve.[28] Energy calibrations were made using combinations of standard sources as internal standards during data acquisition.[28]

Analysis of the γ-ray spectra was accomplished using a computer code, GAMANAL, developed by Gunnink, Levy, and Niday.[29] Half-life data were used to assign γ rays to ^{95}Tc^{g} on ^{95}Tc^{m} in all instances. Tables I and II contain the detailed results of γ-ray energies and intensities for 20-h ^{95}Tc^{g} and 61-day ^{95}Tc^{m}, respectively. Contributions to the ^{95}Tc^{m} spectrum due to decay through the isomeric transition and ^{95}Tc^{g} have been subtracted from Table II. In a number of instances upper limits on the intensity of unobserved transitions are reported and designated by parentheses as are uncertain assignments of some very low intensity γ rays. We show a Compton suppression spectra in Fig. 2.

TABLE II. γ rays assigned to ^{95}Tc^{m} decay.

$E_\gamma(\Delta E_\gamma)$ (keV)	$I_\gamma(\Delta I_\gamma)$ [a]	Assignment
(54.88)	<0.003	(821→766)
204.12(1)	1000(2)	204→0
218.66(8)	0.68(3)	1039→821
(245.83(9)	(0.028(7)	(1302→1057)
252.95(1)	9.66(7)	1039→786
(263)	(<0.002)	(1302→1039)
291.67(4)	0.088(8)	
318.27(10)	0.016(6)	(1620→1302)
510.98(1)	6.99(7)	$\beta+$
(515.60(40)	(0.005(5)	(1302→786)
563.48(6)	0.15(2)	1620→1057
582.07(1)	473.7(8)	786→204
589.29(25)	0.016(4)	
616.49(2)	20.3(2)	821→204
623.29(15)	0.09(3)	
786.18(2)	136.9(7)	786→0
799.60(15)	0.023(8)	1620→821
820.61(1)	74.5(1)	821→0
835.13(1)	421(3)	1039→204
852.60(2)	0.329(8)	1057→204
1039.25(2)	43.9(4)	1039→0
1056.79(2)	0.140(5)	1057→0
(1098)	<0.0003	(1302→204)
(1165.50)	<0.0015	(1369→204)
1222.00(3)	0.132(3)	1426→204
(1302)	<0.0003	(1302→0)
1369.75(15)	0.0021(5)	1370→0
1416.09(8)	0.029(1)	1620→204
1426.11(15)	0.0004(3)	1426→0
1620.20(4)	0.59(3)	1620→0
1660.27(25)	0.000 08(5)	1661→0

[a] Normalized to 1000 at 204.12 keV.

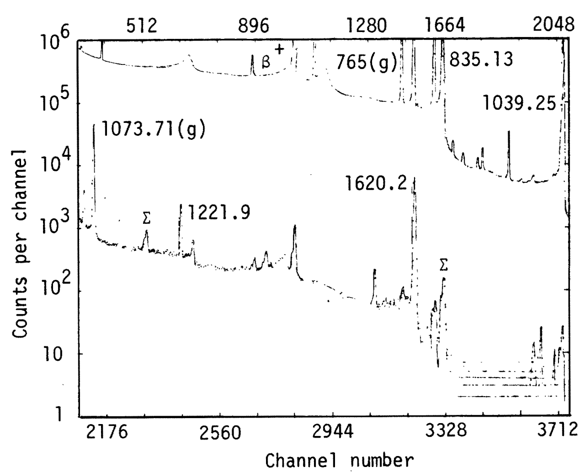

FIG. 2. Compton suppression spectra of ^{95}Tc^{m}(N.B., g represents a photopeak from the ground state decay that is in transient equilibrium while $\sum$ represents a sum peak which for this Compton suppression spectrometer has a characteristic shape different from that of a true photopeak.

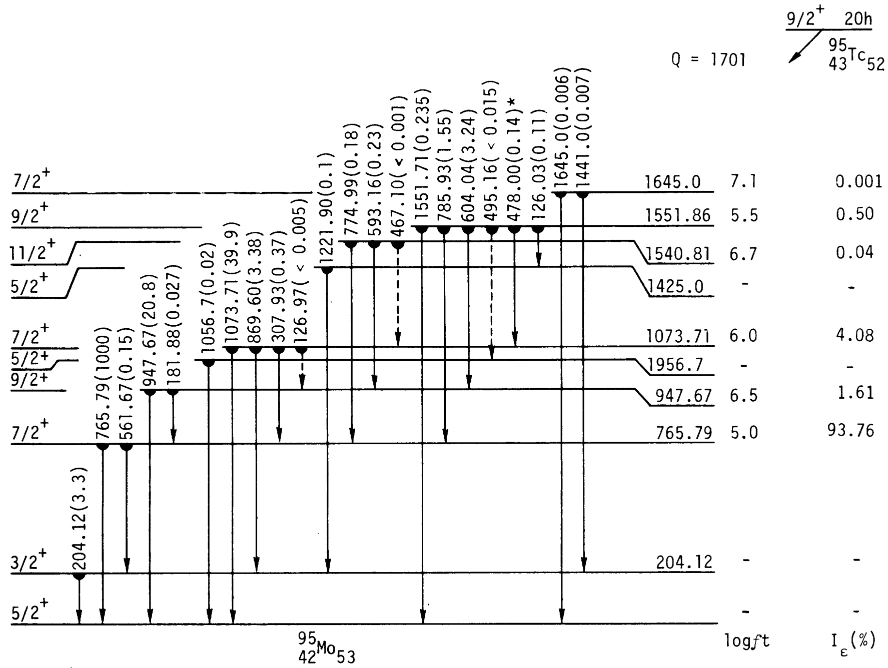

FIG. 3. Level scheme of ^{95}Mo as populated in decay of 20-h ^{95}Tc^{g}. Energies are in keV and relative γ-ray intensities are shown in parentheses. To the left of each level is shown the J^{π} assignment and to the right the electron capture feed percentage and logft value.

In general our results augment those of recent investigations with some 20 additional γ rays reported here for the first time. We did not observe the 844.1-keV γ ray reported recently by Antoneva *et al.*[20]

III. DECAY SCHEMES

Decay schemes that best accomodate the experimental data for ^{95}Tc^{g} and ^{95}Tc^{m} are shown in Figs. 3 and 4. Logft values are shown to the right of each level together with the percentage feed by electron capture and position decay where appropriate. A few remarks about the calculation of logft values for ^{95}Tc^{m} decay to the ground and 204.12-keV levels of ^{95}Mo are necessary since there exists disagreement as to the amount of β^+ and ϵ feed to these levels. Cretzu, Hohmuth, and Schintlmeister[30] reported a total positron branch for ^{95}Tc^{m} decay of $(0.42 \pm 0.03)\%$ based on their decay scheme. Later, Bond and Jha[31] concluded that the positron branch was $(0.47 \pm 0.06)\%$ from a comparison of annihilation coincidence rates with 835γ-204γ and 582-204γ coincidence rates. Medsker and Horen[14] reviewed the available data on ^{95}Tc^{m} decay up to 1972 and pointed out that the apparent decay scheme is consistent with a β^+ feed of only 0.22%, while the most recently published study by Antoneva *et al.*[20] suggests a value of 0.31%. We have carefully measured the annihilation rate of a chemically-separated, electrodeposited ^{95}Tc^{m} source in order to estimate the β^+ branch and arrive at a value of $(0.24 \pm 0.03)\%$ calculated on the basis of the decay scheme shown in Fig. 4. Inherent in the logft calculation is a degree of uncertainty due to the necessary use of the theoretical ratio $\beta^+/\epsilon = 54$ for an assumed first-forbidden unique transition to the ^{95}Mo ground state,[32] the theoretical ratio $\beta^+/\epsilon = 62$ for the first-forbidden transition to the 204.12-keV state,[30] and the experimental value for the relative positron feed to the ground state and the 204.12-keV state, $\beta_0/\beta_{204} = 1.2 \pm 0.2$ as reported by Antoneva *et al.*[20] Alternatively one can use $\beta_0/\beta_{204} = 2.5$ from Ref. 30. We prefer the former value since the estimated total β^+ branch calculated using $\beta_0/\beta_{204} = 1.2$ is 0.32% in somewhat better agreement with our experimental result of 0.24% than one gets using $\beta_0/\beta_{204} = 2.5$, which leads to 0.47% for the branch. From these values and the tables of Gove and Martin[32] we calculate a Q_{EC} value for ^{95}Tc^{m} of 1740 ±15 keV.

IV. LEVEL ASSIGNMENTS FOR ^{95}Mo

A comprehensive compilation of the literature up to 1972 on ^{95}Mo levels has been published by Medsker and Horen.[14] We will limit our remarks to levels which have been observed in radioactive decay for the first time in our experiments or to established levels where we have gained some addi-

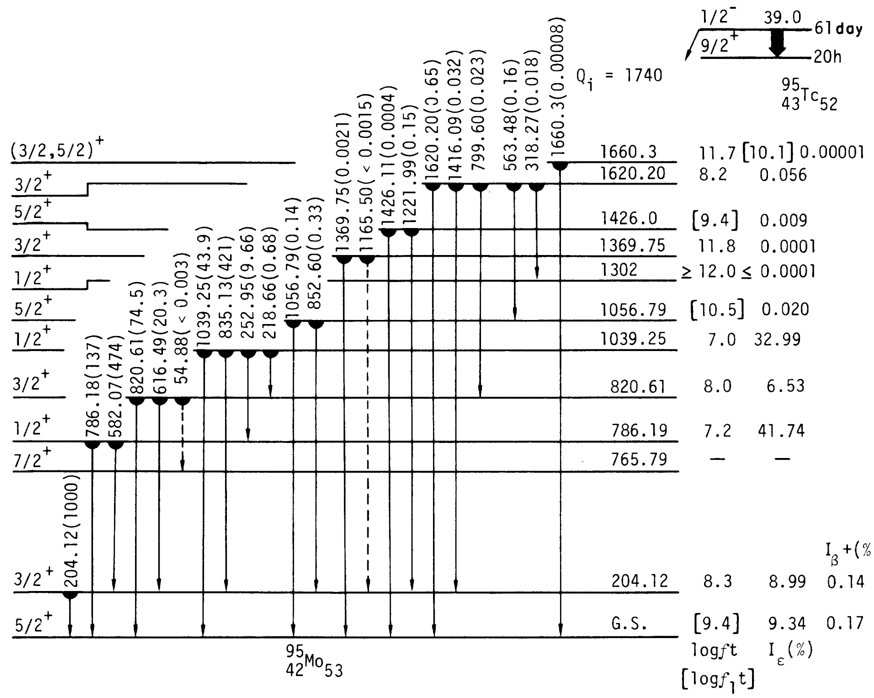

FIG. 4. Level scheme of ^{95}Mo as populated in decay of 60-day ^{95}Tc^m. Energies are in keV and relative γ-ray intensities are in parentheses. The J^{π} assignment is shown to the left of each level and the total electron capture β^+ feed percentage and logft [logf_1t] values are found to the right.

tional understanding. First, we comment on four energy levels known prior to our work but which were not seen in previous radioactive decay experiments with energies of 1302, 1369.75, 1540.81, and 1660.3 keV. We follow this by a discussion of spin and parity assignments for the 1425.84-, 1551.86-, and 1620.20-keV levels and, finally, a new level at 1645 keV is proposed.

$\frac{1}{2}^+$ level at 1302 keV. We have observed three low intensity γ rays with energies of 245.83, 318.27, and 515.60 keV following decay of ^{95}Tc^m. These may represent the decay of level at 1302 keV in ^{95}Mo. Moorhead and Moyer[33] and Diehl *et al.*,[34] have reported a level at 1310 keV which they both assigned as $\frac{1}{2}^+$ based on (d,p) reaction experiments. No other evidence for this level is found in the literature. Hence we consider it only as a tentative assignment.

$\frac{3}{2}^+$ level at 1369.75 keV. We have measured a 1369.75-keV γ ray in our ^{95}Tc^m decay experiments which we assign as deexciting a level of the same energy. The (d,p) reaction experiments[33,34] observe a level at 1376 keV which was populated by an $l=2$ transition. Mesko *et al.*,[35] have measured the (α, xn) reaction γ-ray spectrum of ^{95}Mo in beam as a function of α-bombardment energy. They reported a 1369.8-keV γ ray which they associated with the 1376-keV level observed in the (d,p) experiments. A $(\frac{3}{2})^+$ assignment for this level was supported by γ-ray intensity data compiled as a function of bombardment energy. We believe that all three experiments are observing the same level. The logft value of 11.8 calculated from our

TABLE III. Conversion electron intensities, conversion coefficient, and multipolarities.

E (transition)	I_{ce^-}	α ($\times 10^3$)	Λ
252 K	380(15)	12.0(4)	$M1 + (29\pm2)\%\ E2$
582 K	3600(150)	2.28(8)	$M1$
L	420(20)	0.26(1)	
616 K	185(10)	2.31(12)	$M1+E2$
L	15(1)	0.19(1)	
765 K	210(11)	1.28(9)	$M1+E2$
L	26(2)	0.15(2)	
786 K	523(20)	1.16(4)	$E2$
L	66(3)	0.14(1)	
M	13(1)	0.007(1)	
820 K	261(13)	1.06	$M1+E2$
L	35(3)	0.14(2)	
835 K	1450(60)	1.050(43)	$M1 + 0.14\%\ E2$
L	210(11)	0.152(8)	
M	63(2)	0.046(2)	
(869 K)	(~1)	(~1)	($E2$)
947 K	2.2(1)	0.7(1)	$M1+E2$
1039 K	80(4)	0.6(1)	$M1+E2$
1073 K	3.9(5)	0.57(7)	$E2$
L	0.4(1)	0.05(1)	

$^{95}Tc^m$ decay scheme is in agreement with the $\frac{3}{2}^+$ assignment for this level although a $\frac{5}{2}^+$ assignment cannot be excluded.

$\frac{11}{2}^+$ level at 1540.81 keV. We have observed two γ rays of energy 593.16 and 774.99 keV in $^{95}Tc^g$ decay which we assign as depopulating a level at 1540.81 keV. Mesko *et al.*,[35] have measured γ rays of the same energy and on the basis of strong evidence proposed a $\frac{11}{2}^+$ level at 1541.2 keV. Youngblood and co-workers[23,24] have noted a high l-value component in their (d,p) and (d,t) studies for their 1540-keV angular distribution. We note here that the deduced logft value of 5.5 and the absence of deexciting transitions to states of spin lower than $\frac{7}{2}^+$ support the $\frac{11}{2}^+$ assignment.

$(\frac{3}{2},\frac{5}{2})^+$ level at 1660.3 keV. A single γ ray of energy 1660.3 keV is proposed to deexcite a level of the same energy in ^{95}Mo. Diehl *et al.*,[34] reported evidence for a level at 1670 keV populated by an $l=2$ transition in the (d,t) reaction. No other experimental evidence has been published for this level. The calculated logft [logf_1t] values of 11.7 [10.1] are inconclusive as to whether the level assignment is $\frac{3}{2}^+$ or $\frac{5}{2}^+$.

$\frac{5}{2}^+$ level at 1426.0 keV. We have detected γ rays of energy 126.03 and 1221.90 keV in $^{95}Tc^g$ decay and 1221.99 and 1426.11 keV in $^{95}Tc^m$ decay which taken together provide evidence for a level at 1426.0 keV with a $\frac{5}{2}^+$ assignment. Moorhead and Moyer[33] and Diehl *et al.*[34] reported population of a level at about 1432 keV in ^{95}Mo by $l=2$ transitions in the (d,p) and (d,t) reactions, respectively. Although they suggested a tentative $\frac{3}{2}^+$ assignment the later in-beam reaction γ-ray experiments of Mesko *et al.*[35] were more consistent with a $\frac{5}{2}^+$ assignment. Recently, Antoneva *et al.*[20] reported the first evidence for population of the 1426.0-keV level in radioactive decay with the observation of a 1222.4-keV γ ray connecting to the 204.12-keV level. Our observations of two γ rays, 1221.99 and 1426.11 keV, which depopulate the 1426.0-keV level, and, in particular, a 126.03-keV γ ray, which we assign on the basis of energy fit as feeding the 1426.0-keV level from the 1551.86-keV $\frac{9}{2}^+$ state, add further support to the $\frac{5}{2}^+$ assignment.

$\frac{9}{2}^+$ level at 1551.86 keV. Our observations of five γ rays following $^{95}Tc^g$ decay, which depopulate a level at 1551.86 keV in ^{95}Mo together with a calculated logft value of 5.5, support a $\frac{9}{2}^+$ assignment for this level. Chilosi, Eichler, and Aras[36] first proposed a level at this energy based on γ-γ coincidence measurements using NaI detectors. They observed the decay of the 1551.86-keV level to the 947.67-keV $\frac{9}{2}^+$ level. Mesko *et al.*[35] measured an additional decay branch to the 765.79-keV $\frac{7}{2}^+$ level in their in-beam experiments. Recently, Krämer and Huber[21] reported two new γ-ray branches to the $\frac{5}{2}^+$ ground state and the 1073.71-keV $\frac{7}{2}^+$ level. We confirm the previous data and include one additional γ ray, 126.03 keV, in our decay scheme (Fig. 3). The logft value of 5.5 is consistent with a normal-allowed β transition from $^{95}Tc^g$ which together with the $l=4(d,p)$ and (d,t) angular distributions[23,24] and γ-ray data restrict the 1551.86-keV assignment to $\frac{7}{2}^+$ or $\frac{9}{2}^+$. We prefer the latter assignment since there is no apparent decay branch to the 204.12-keV $\frac{3}{2}^+$ level.

$\frac{3}{2}^+$ level at 1620.20 keV. We report the observation of five γ rays following $^{95}Tc^m$ decay which depopulate a level at 1620.20 keV in ^{95}Mo. Our γ-ray data and calculated logft value of 8.2 suggest a $\frac{3}{2}^+$ assignment for this level. Moorhead and Moyer[33] and Diehl *et al.*[34] reported population of a level at about 1625 keV in ^{95}Mo by $l=2$ transitions in (d,p) and (d,t) reaction experiments. Several experiments have reported observation of a 1620-keV γ ray following $^{95}Tc^m$ decay, which was presumed to deexcite this level to ground. Recently, Antoneva *et al.*[20] found a 1416.3-keV transition to the 204.12-keV $\frac{3}{2}^+$ level. We observe three additional γ rays connecting the 1620.20-keV level to the 820.61-keV $\frac{3}{2}^+$, 1056.79-keV $\frac{5}{2}^+$, and 1302-keV $\frac{1}{2}^+$ levels. The apparent logft value of 8.2 calculated from our decay scheme (Fig. 4) is consistent with a first-forbidden β transition and agrees reasonably with values for known $\frac{3}{2}^+$ states at 204.12 keV, 8.3 and 820.61 keV, 8.0 but not with the 11.9 value for the 1369.75-keV level. Alternatively, if one assumes the 1620.20-keV level to be $\frac{5}{2}^+$ the logf_1t value is 6.8 which is too low for a first-forbidden unique β transition. We thus prefer a $\frac{3}{2}^+$ assignment for the 1620.20-keV level.

$\frac{7}{2}^+$ state at 1645.0 keV. A $\frac{7}{2}^+$ level at 1645.0 keV which is populated in β decay of $^{95}Tc^g$ is proposed here for the first time. We observe two very weak γ rays with energy 1441.0 and 1645.0 keV which depopulate this level to the ground and first excited states of ^{95}Mo. The calculated logft value of 7.1 is consistent with allowed or first-forbidden β transitions which suggests possible assignments of $\frac{7}{2}^{\pm}$, $\frac{9}{2}^{\pm}$, or $\frac{11}{2}^{\pm}$ for the 1645.0-keV level. The γ-ray decay to the 204.12-keV $\frac{3}{2}^+$ state excludes all spin and parity assignments except $\frac{7}{2}^+$ for this level. Bindal *et al.*[23,24] have observed a level at approximately this energy with an $l=4$ angular distribution in their (d,p) and (d,t) studies as do Schoonover *et al.*[27] in their (^{3}He, α) studies.

V. DISCUSSION

Theoretical approaches to ^{95}Mo have been attempted in shell-model calculations[37,38] and in descriptions based on coupling restricted shell-model particles or quasiparticles to vibrations.[31,39-42] In

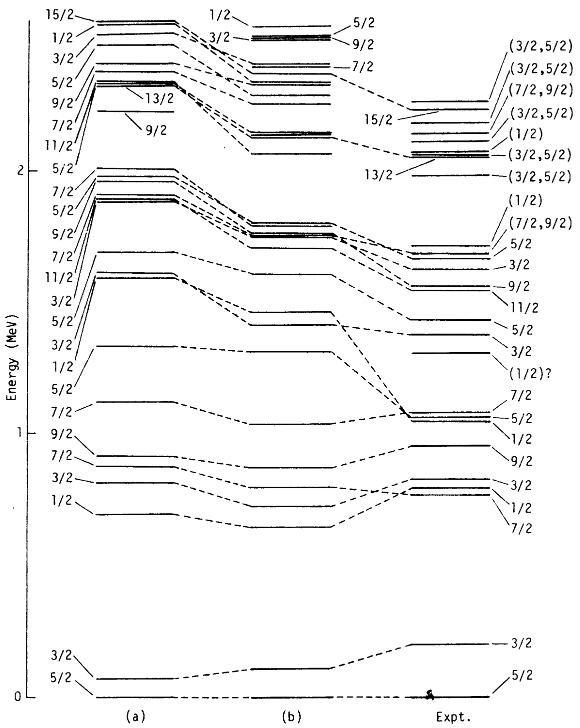

FIG. 5. The calculated and experimental positive-parity spectra of ^{95}Mo. To the left: the calculated spectrum is presented for natural parametrization, without any adjustable parameter. In the middle (b): the result of calculation, with phonon energy and $g_{7/2}$ single-particle position lowered by 20% with respect to natural parametrization. To the right: experimental states—results of the present experiment are shown below and those of Ref. 14 above 1661 keV.

Ref. 42, two arbitrarily selected three-hole configurations $(d_{5/2}{}^{-3})\frac{3}{2}$, $(d_{5/2}{}^{-3})\frac{5}{2}$ have been coupled to quadrupole vibrations. In Ref. 39, a three-neutron valence-shell cluster consisting of three neutrons, moving in the 50-82 shell, has been coupled to quadrupole vibrations; the ^{94}Mo nucleus has been treated on the same footing, by coupling a two-neutron valence-shell cluster to quadrupole vibrations. The interplay of a dynamical shell-model cluster and a vibrational degree of freedom generally gives rise to the coexistence of quasivibrational, quasirotational, and clustering phenomena, both in odd- and even-A nuclei.[2,3] In this paper we extend the calculation from Ref. 39 in the light of new data obtained in the present experiments. The parametrization used is the same as in Ref. 39; it is taken in a simple-minded way directly from experiment. The neutron single-particle levels are taken as determined by the ^{92}Mo$(d,p)^{93}$Mo reaction in Ref. 33: $\epsilon(s_{1/2})-\epsilon(d_{5/2})=1.55$ MeV, $\epsilon(g_{7/2})-\epsilon(d_{5/2})=1.50$ MeV, $\epsilon(d_{3/2})-\epsilon(d_{5/2})=1.89$ MeV, $\epsilon(h_{11/2})-\epsilon(d_{5/2})=2.22$ MeV. The experimental energy of the first excited state in ^{92}Mo is taken as the phonon energy $\hbar\omega_2=1.51$ MeV. The pairing strength is $G=23/A$ and the particle-vibration coupling strength $\alpha=0.8$ is determined by using the experimental value $B(E2)$ $(2_1\rightarrow 0_1)$ from ^{92}Mo and the usual estimate $\langle k\rangle=50$ MeV (this selection is referred to as natural parametrization). In this treatment, without any adjustable parameter, the cluster-vibration Hamiltonian is diagonalized in the basis $|[(j_1j_2)J_{12},j_3]J,NR;I\rangle$. Here N represents the number and R the angular momentum of phonons, J is the angular momentum of the three-neutron cluster, and I is the total angular momentum. The results are to some extent sensitive to the truncation of the phonon space. In Ref. 39, the calculation was performed with the truncation of basis states at definite energy, so that the maximum dimension of the Hamiltonian matrix was 100. In the present paper, the truncation energy is extended to the maximum dimension of 150 which results in the calculated spectrum as presented in Fig. 5(a). The extension of the truncation energy causes an additional shift of states typically by about 0.1 MeV, leading to a somewhat more compressed spectrum. However, the theoretical spectrum is still too stretched in comparison with the experimental one. To account for this stretching, we have considered the phonon energy and the $g_{7/2}$ single-particle energy to be decreased by 20% with respect to their values in natural parametrization. The calculated spectrum obtained in this way is presented in Fig. 5(b). The electromagnetic properties for level deexcitation were obtained by using the wave functions calculated in natural parametrization. The effective charges and gyromagnetic ratios are as follows: $e^{\text{s.p.}}=0.5$, $e^{\text{VIB}}=2.2$, $g_R=Z/A$, $g_l=0$, $g_s=-2.$[2,3,39] In Table IV we present the calculated $B(E2)$, $B(M1)$ values and branching ratios and compare them with the present experimental results.

Combination of theoretical considerations and experimental evidence indicates that the nine lowest experimental positive-parity states have corresponding theoretical partners. In addition, the experimental states at 1541 and 1552 keV seem to correspond to the theoretical states $\frac{11}{2}{}^+_1$ and $\frac{9}{2}{}^+_2$, respectively. If the *tentatively assigned* low-energy γ rays are correct, then the possible experimental state at 1302 keV seems not to be a model state, but a state of different character; this level decays most strongly by 295.65-keV transition, while the calculation does not provide a state of corresponding decay pattern.

The calculated wave functions are of a rather complex structure because both the particle-vibration and the pairing strength are not weak: however, there are a few pronounced components in each state. For example, in a few low-lying states the components with amplitudes larger than 4% are as follows:

TABLE IV. Comparison of the experimental and theoretical branching ratios in ^{95}Mo. The calculated transitions from each state are normalized to the corresponding experimental transition with strongest intensity. The available experimental static moments are as follows: $Q(\frac{5}{2}_1) = -0.019 + 0.012$, (Ref. 43) -0.075 ± 0.025 eb (Ref. 44); $\mu(\frac{5}{2}_1) = -0.91\mu_N$, and $\mu(\frac{3}{2}_1) = -0.42\mu_N$. The corresponding calculated values are $Q(\frac{5}{2}_1) = -0.4$ eb, $\mu(\frac{5}{2}_1) = 0.61\mu_N$ and $\mu(\frac{3}{2}_1) = -0.30\mu_N$, respectively. The calculated $B(E2)$ and $B(M1)$ are expressed in units of e^2b^2 and $\mu_N{}^2$, respectively. The transition probability for a pure $E2$ transition is calculated from the theoretical $B(E2)$ by the formula:

$T(E2)(I_i \to I_f) = 1.22(E_\gamma)^5 B(E2)(I_i \to I_f) \times 10^{13}$/sec.

For pure $M1$ transition the transition probability is the following:

$T(M1)(I_i \to I_f) = 1.76(E_\gamma)^3 B(M1)(I_i \to I_f) \times 10^{13}$/sec.

For the mixed $E2+M1$ transition the transition probability is the following:

$T(E2+M1)(I_i \to I_f) = [1.22(E_\gamma)^5 B(E2)(I_i \to I_f) + 1.76 E_\gamma{}^3 B(M1)(I_i \to I_f)] \times 10^{13}$/sec,

where E_γ is the transition energy in MeV.

Transition	Experiment E (keV)	I	$B(E2)$ (e^2b^2)	Theory[a] $B(M1)(\mu_N{}^2)$	I
$\frac{3}{2}_1-\frac{5}{2}_1$	204	1000	0.0716	0.039	1000
$\frac{7}{2}_1-\frac{5}{2}_1$	766	1000	0.0024	0.013	1000
$\frac{7}{2}_1-\frac{3}{2}_1$	562	0.15	0.000 04		0.25
$\frac{1}{2}_1-\frac{5}{2}_1$	786	136.9	0.0206		1790
$\frac{1}{2}_1-\frac{3}{2}_1$	582	437.7	0.0013	0.005	437.7
$\frac{3}{2}_2-\frac{5}{2}_1$	821	74.5	0.0003	0.096	74.5
$\frac{3}{2}_2-\frac{3}{2}_1$	617	20.3	0.0101	0.039	13.7
$\frac{3}{2}_2-\frac{7}{2}_1$	55	<0.003	0.052		0.000 03
$\frac{9}{2}_1-\frac{5}{2}_1$	948	20.8	0.0373		20.8
$\frac{9}{2}_1-\frac{7}{2}_1$	182	0.027	0.000 02	0.013	0.10
$\frac{1}{2}_2-\frac{5}{2}_1$	1039	43.9	0.0054		7
$\frac{1}{2}_2-\frac{3}{2}_1$	835	421	0.0002	0.434	421
$\frac{1}{2}_2-\frac{1}{2}_1$	253	9.66		0.033	0.9
$\frac{1}{2}_2-\frac{3}{2}_2$	219	0.68	0.0061	0.021	0.4
$\frac{5}{2}_2-\frac{5}{2}_1$	1057	0.140	0.0096	0.017	0.089
$\frac{5}{2}_2-\frac{3}{2}_1$	853	0.329	0.0034	0.170	0.329
$\frac{5}{2}_2-\frac{7}{2}_1$	291	0.088	0.0029	0.001	0.0001
$\frac{7}{2}_2-\frac{5}{2}_1$	1074	39.9	0.027	0.014	39.9
$\frac{7}{2}_2-\frac{3}{2}_1$	870	3.38	0.015		4.7
$\frac{7}{2}_2-\frac{7}{2}_1$	307	0.37	0.002	0.079	2.1
$\frac{11}{2}_1-\frac{7}{2}_1$	775	0.18	0.0256		0.09
$\frac{1}{2}_1-\frac{9}{2}_1$	593	0.23	0.0032	0.064	0.23
$\frac{11}{2}_1-\frac{7}{2}_2$	467	0.14	0.0039		0.001
$\frac{9}{2}_2-\frac{5}{2}_1$	1552	0.235	0.0004		0.21
$\frac{9}{2}_2-\frac{7}{2}_1$	786	1.55	0.0051	0.002	0.18
$\frac{9}{2}_2-\frac{9}{2}_1$	604	3.24	0.0035	0.165	3.24
$\frac{9}{2}_2-\frac{5}{2}_2$	497	<0.015	0.0085		0.016
$\frac{9}{2}_2-\frac{7}{2}_2$	478	0.14	0.0039	0.012	0.12
$\frac{9}{2}_2-\frac{5}{2}_3$	126	0.11	0.0057		0.00
$\frac{3}{2}_3-\frac{5}{2}_1$	1370	0.0023	0.0009	0.034	0.0023
$\frac{3}{2}_3-\frac{3}{2}_1$	1166	<0.0015	0.0132	0.042	0.0022

$$|\tfrac{5}{2}_1\rangle = 0.67\,|(d_{5/2}{}^3)\tfrac{5}{2}\rangle - 0.35\,|(d_{5/2}{}^3)\tfrac{3}{2},12\rangle - 0.25\,|(d_{5/2}{}^3)\tfrac{9}{2},12\rangle\;,$$

$$|\tfrac{3}{2}_1\rangle = 0.55\,|(d_{5/2}{}^3)\tfrac{5}{2},12\rangle + 0.48\,|(d_{5/2}{}^3)\tfrac{3}{2}\rangle\;,$$

$$|\tfrac{7}{2}_1\rangle = -0.48\,|(d_{5/2}{}^3)\tfrac{5}{2},12\rangle + 0.24\,|(d_{5/2}{}^3)\tfrac{3}{2},12\rangle - 0.25\,||(d_{5/2}{}^2)0,g_{7/2}|\tfrac{7}{2}\rangle + 0.38\,||(d_{5/2}{}^2)4,s_{1/2}|\tfrac{7}{2}\rangle\;,$$

$$|\tfrac{7}{2}_2\rangle = -0.52\,||(d_{5/2}{}^2)0,g_{7/2}|\tfrac{7}{2}\rangle + 0.30\,||(d_{5/2}{}^2)0,g_{7/2}|\tfrac{7}{2},12\rangle + 0.21\,||(d_{5/2}{}^2)2,g_{7/2}|\tfrac{7}{2},12\rangle + 0.25\,||(d_{5/2}{}^2)2,g_{7/2}|\tfrac{11}{2},12\rangle$$
$$-0.23\,||(d_{5/2}{}^2)2,d_{3/2}|\tfrac{7}{2}\rangle + 0.32\,||(d_{5/2}{}^2)0,d_{3/2}|\tfrac{3}{2},12\rangle\;.$$

It is useful to look at the zeroth-order classification as a guideline for qualitative discussion. In the zeroth-order approximation for the particle-vibration coupling, also including diagonal matrix elements of pairing, there are 10 states below 1.55 MeV: $(d_{5/2}{}^3)/\frac{5}{2}{}_1^{(0)}$ at -0.75 MeV; $(d_{5/2}{}^3)\frac{3}{2}{}_1^{(0)}, \frac{9}{2}^{(0)}$ at 0 MeV; $[(d_{5/2}{}^2)0, g_{7/2}]\,\frac{7}{2}{}_1^{(0)}$ at 1.50–0.75 = 0.75 MeV; $[(d_{5/2}{}^3)\frac{5}{2}, 12]\,\frac{1}{2}{}_1^{(0)}, \frac{3}{2}{}_2^{(0)}, \frac{5}{2}{}_2^{(0)}, \frac{7}{2}{}_2^{(0)}, \frac{9}{2}{}_2^{(0)}$ at 1.51-0.75 = 0.76 MeV; $[(d_{5/2}{}^2)0, s_{1/2}]\,\frac{1}{2}{}_2^{(0)}$ at 1.55-0.75 = 0.80 MeV. Indeed, the ordering of low-lying experimental positive-parity states bears pronounced resemblance to this zeroth-order classification. In the experiment, the lowest-lying doublet $\frac{5}{2}_1, \frac{3}{2}_1$ is followed by a group of seven positive parity states: $\frac{7}{2}_1$, $\frac{1}{2}_1$, $\frac{3}{2}_2$, $\frac{9}{2}_1$, $\frac{1}{2}_2$, $\frac{5}{2}_2$, and $\frac{7}{2}_2$. Starting from the zeroth-order picture, the lowering of the $\frac{3}{2}_1$ state and the shift upwards of the $\frac{9}{2}_1$ state stand out as obvious effects. A consequence of nondiagonal matrix elements of pairing is that the states involved in zeroth order from a cluster of seniority one will be lowered with respect to the states involving a cluster of seniority three. This leads to an additional shift upwards of the states based on $(d_{5/2}{}^3)\frac{3}{2}{}_1^{(0)}$ and $(d_{5/2}{}^3)\frac{9}{2}{}_1^{(0)}$ with respect to the states based on the other low-lying clusters and multiplets in the zeroth-order spectrum. On the other hand, it has generally been shown that the pronounced effect of the cluster-vibration interaction is the strong lowering of the state of spin $I=j-1$ relative to the state arising from $(j^3)I=j$ in zeroth order. In the cluster-vibration model, this $I=j-1$ state has a pronounced collective character, which is reflected in the strong $I=j-1 \rightarrow (j^3)I=j$ $E2$ transition. For higher spins and stronger coupling, the $I=j-1$ state may be lowered even below the $I=j$ state (the so-called "$I=j-1$ anomaly"), as in the case of ^{51,55}Mn, ^{107,109,111}Ag, and ^{203}At.[3] The one-phonon multiplet $[(j^3)j, 12]I=j-1$ plays an essential role in the lowering of the $I=j-1$ state. In the case of ^{95}Mo ($j=\frac{5}{2}$), such an effect appears for the $\frac{3}{2}_1$ state and consequently this state is lowered close to the $\frac{5}{2}_1$ ground state. Thus, out of 10 lowest-lying positive-parity states in the zeroth-order approximation, we expect the following qualitative pattern: low-lying doublet $\frac{5}{2}_1, \frac{3}{2}_1$ followed by another group of 8 states, out of which the $\frac{9}{2}_2$ state is shifted upwards. This is in excellent qualitative agreement with experiment. The analogy between experiment and the zeroth-order cluster-vibration classification can be pursued even further. The 10 lowest-lying zeroth-order states are immediately followed by the clusters $[d_{5/2}{}^2)0, d_{3/2}]\frac{3}{2}{}_3^{(0)}$ at 1.89-0.75 = 1.12 MeV and $[(d_{5/2}{}^2)2, g_{7/2}]\frac{3}{2}{}_4^{(0)}, \frac{5}{2}{}_3^{(0)}, \frac{7}{2}{}_3^{(0)}, \frac{9}{2}{}_3^{(0)}, \frac{11}{2}{}_1^{(0)}$ at 1.50 MeV; in this energy region, the following states have been identified experimentally: 1370 $(\frac{3}{2}, \frac{5}{2})$, 1426 $(\frac{5}{2}, \frac{3}{2})$, 1541 $(\frac{11}{2})$, 1552 $(\frac{9}{2})$, 1620 $(\frac{3}{2})$.

Although the coupling strength in the cluster-vibration coupling model is not weak, which is reflected in the rather mixed character of the wave functions, it is still possible to discuss qualitatively many properties of low-lying states based on zeroth-order classification and leading-order effects. Such an approach is based on the systematic interference occurring among many higher-order terms.[3] The same type of interference is also reflected in the electromagnetic properties within the cluster-vibration model. In zeroth-order classification, $B(E2)(\frac{7}{2}{}_1^{(0)} \rightarrow \frac{5}{2}{}_1^{(0)}) \ll B(E2)(\frac{7}{2}{}_2^{(0)} \rightarrow \frac{5}{2}{}_1^{(0)})$, because the first transition is of single-particle character, being additionally reduced by the spin-flip approximate selection rule, while the second transition is of collective character, changing the phonon number by one. Experimental data clearly reveal this lowest-order effect. It should be stressed, however, that the two corresponding calculated lowest-lying $\frac{7}{2}$ states are rather mixed. This is reflected in the instability of the calculated transition moments to the $\frac{5}{2}_1$ and $\frac{3}{2}_1$ states with respect to parametrization and truncation. One of the two $\frac{7}{2}$ states acts as a more collective state then the other, but their relative ordering is sensitive to details of the calculation and is reversed for extended truncation. The $\frac{3}{2}_1$ state is of collective character, being predominantly a mixture of $\frac{3}{2}{}_1^{(0)}$ and $\frac{3}{2}{}_2^{(0)}$states, which both contribute coherently to the $E2$ transition moment for the $\frac{3}{2}_1 \rightarrow \frac{5}{2}_1$ transition.

As a result of the delicate destructive interference, the $E2$ transition moment for the transition which is classified as $\frac{7}{2}{}_1^{(0)} \rightarrow \frac{3}{2}_1$, may be strongly hindered, as in the case presented here; however, slight changes in details of calculation may sizably affect the quantitative value. The experimental intensity of the $\frac{7}{2}_1 \rightarrow \frac{3}{2}_1$ transition is smaller by four orders of magnitude than that of the $\frac{7}{2}_1 \rightarrow \frac{5}{2}_1$ transition. This peculiar hindrance arises also in the cluster-vibration calculation due to strong incoherence.

Taking into account the neglected part of dynamical correlations and the sensitivity to parametrization and truncation of the present calculation, the numerical results should not be interpreted too rigidly. This should particularly be kept in mind for weaker transitions involving a large degree of incoherence.

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