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ΔK forbiddenness in neutron capture resonances in ^{177}Lu

R. K. Sheline
Departments of Chemistry and Physics, Florida State University, Tallahassee, Florida 32306

L. Bergholt, M. Guttormsen, J. Rekstad, and T. S. Tveter
Department of Physics, University of Oslo, Oslo, Norway

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Neutron capture resonances produced in ^{177}Lu by thermal neutrons are shown to gamma decay with intensities which are dependent on a ΔK selection rule. The difference between ΔK-forbidden (and ΔK-allowed) transition rates, corrected for the energy dependence, when summed over all forbidden (and allowed) transitions and divided by the number of transitions is 1.37 photons/10^7 neutron captures/MeV^5 for the forbidden transitions and 5.49 photons/10^7 neutron captures/MeV^5 for the allowed transitions which gives a ratio between forbidden and allowed transitions of 0.26. If we require that allowed and forbidden transitions only be compared within the same spin and parity group, many transitions are excluded because there are no forbidden transitions to negative parity states. The average values for the forbidden and allowed transition ensembles are then 0.59 and 1.31, respectively, giving a ratio of forbidden to allowed transition intensities of 0.45.

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I. INTRODUCTION

Recently, evidence has been presented [1,2] which suggests that the gamma decay of neutron resonances produced in thermal and 2 keV neutron capture shows a tendency toward K forbiddenness. This result has elicited considerable opposition [3–5]. The evidence for chaos at relatively low energy [6] implies that the quantum numbers clearly observed at low energy may lose their significance at slightly higher energies. This would seem to imply that ΔK forbiddenness from levels populated in neutron capture in the vicinity of 5–7 MeV should not be observed.

In this paper we look at the evidence for ΔK forbiddenness from the thermal neutron capture in ^{176}Lu with ground state spin 7^- to the neutron resonances in ^{177}Lu. Experimentally, this situation differs from all the previous tests in terms of beginning with an odd-odd target nucleus with very high spin and capturing into resonances which then populate both one- and three-quasiparticle states in ^{177}Lu. We will begin, then, with a discussion of the known level structure of ^{177}Lu, proceed to amplify this structure, and then go on to the study of the relative strength of dipole transitions from the ^{177}Lu capture states to the known levels in ^{177}Lu.

II. THE LEVEL STRUCTURE OF ^{177}Lu

The level structure of ^{177}Lu has been studied by observing neutron capture in ^{176}Lu [7–13], by the beta decay of ^{177}Yb [14,15], by the 160-day isomeric decay of the $23/2^-$ state in ^{177}Lu [16–18], by the (d,p) reaction on ^{176}Lu [8], and by the (^{3}He,d) and (α,t) reactions on ^{176}Yb [19]. This has led to the fairly complex one-quasiparticle and three-quasiparticle level structure shown in Fig. 1. The level structure in Fig. 1 is somewhat more complete than that in Nuclear Data Sheets [20] because we have accepted the very strong cross-sectional evidence from the (d,p), (^{3}He,d), and (α,t) reactions in the assignment of spins, parities, and configurations to levels and because we have also accepted the evidence of the very low log ft values which uniquely identify configurations populated in spin-flip beta transitions from ^{177}Yb. Finally, the level structure in Fig. 1 contains a new rotational band identified in this study. It is shown, together with its gamma transitions to lower levels, in Fig. 2. Justification of this assignment will be postponed until our discussion of three-quasiparticle states is carried out.

A. One-quasiparticle states in ^{177}Lu

A number of one-quasiparticle states are observed in the low-energy level structure of ^{177}Lu. These correspond to the Nilsson levels 7/2[404], 9/2[514], 5/2[402], 1/2[411], 1/2[541], and tentatively 3/2[532] and 1/2[530]. Each of these bands is indicated in Fig. 1. In most cases the band structure continues to quite high spins and energies. For the most part, the level structures are quite regular, except the 3/2[532], 1/2[530], and 1/2[541] bands. Since the K value of none of these bands is greater than 9/2, dipole transitions to any of these bands from the $K^\pi = 13/2^-$ and $15/2^-$ capture states in ^{177}Lu would be ΔK forbidden if the ΔK selection rule is in force.

B. Three-quasiparticle states in ^{177}Lu

Because the odd-odd nucleus ^{176}Lu has a 3.6×10^{10} yr half-life, it serves as an excellent target for both neutron capture and (d,p) reactions. The odd neutron added in these reactions leads to a number of one-proton, two-neutron, three-quasiparticle states. For this reason, a large number of three-quasiparticle rotational bands have been observed in ^{177}Lu. These three-quasiparticle bands are listed in Table I together with their configurations. Each three-quasiparticle configuration gives rise to four rotational bands. The lowest known three-quasiparticle band in ^{177}Lu has the configuration $\pi7/2[404]\nu7/2[514]\nu9/2[624]$. This high-spin, $K^{\pi}=23/2^-$ band has been known for some time because of its long (160 day) isomeric half-life. The decay of this 970.17 keV state has also been important in assigning other states in ^{177}Lu. The other relatively high-spin member of the $\pi7/2[404]\nu7/2[514]\nu9/2[624]$ configuration, with $K^{\pi}=9/2^-$, was tentatively assigned [14] at 1049.5 keV in the decay of ^{177}Yb. The log ft value of 6.4 is that expected for a first forbidden unhindered beta transition. Using existing data [20] we have been able to construct a band on this $K^{\pi}=9/2^-$ bandhead. The observation of states populated in primary (n,γ) decay at 1187.8 and 1348.6 keV and the depopulation of all three members of this band are consistent with their assignment as $9/2^-$, $11/2^-$, and $13/2^-$ members of a $K=9/2^-$ band. The population and decay of this band are shown in Fig. 2.

The next lowest observed three-quasiparticle configuration, which involves an excited proton, has the configuration $\pi9/2[514]\nu7/2[514]\nu9/2[624]$. Only the three lower spin K values are observed for this configuration, as indicated in Table I. The evidence, however, for these three configurations is quite strong because of the three very low log ft values, which imply the allowed, unhindered spin-flip beta decay from ^{177}Tb [21]. Unfortunately, none of the other band members of these three bandheads is known. The third observed three-quasiparticle configuration involves the mixed configuration $\sim 50\%$ $\pi7/2[404] \otimes (K+2)_{\gamma}$ plus $\sim 50\%$

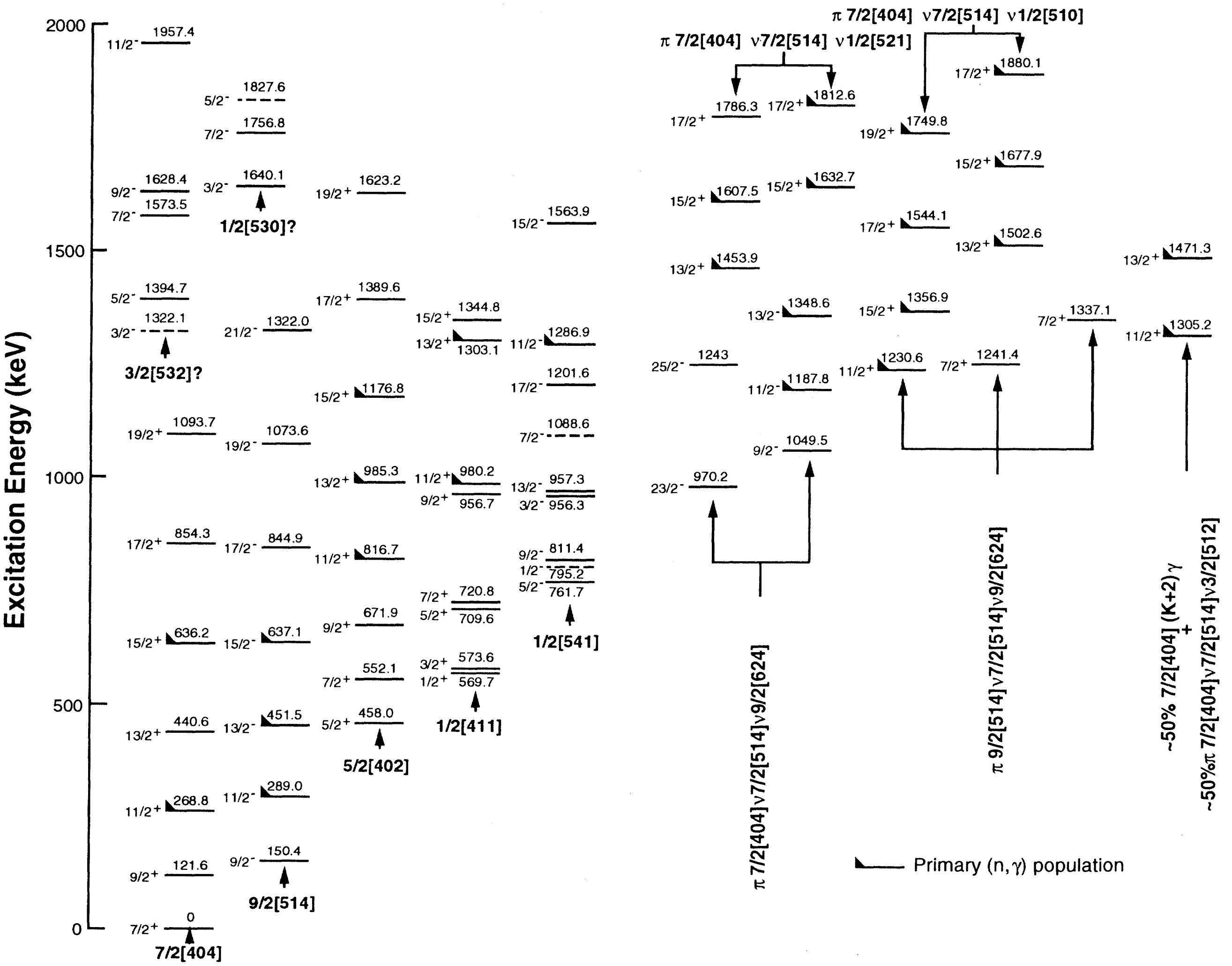

FIG. 1. The level structure of ^{177}Lu as determined from thermal neutron capture, the (d,p), $(^3\mathrm{He},d)$, and (α,t) reactions and the β^- decay of ^{177}Yb. One-quasiparticle states are shown to the left and three-quasiparticle states, separated by a small space, are shown to the right. Primary (n,γ) decay is shown by a flag on the left-hand side of the level.

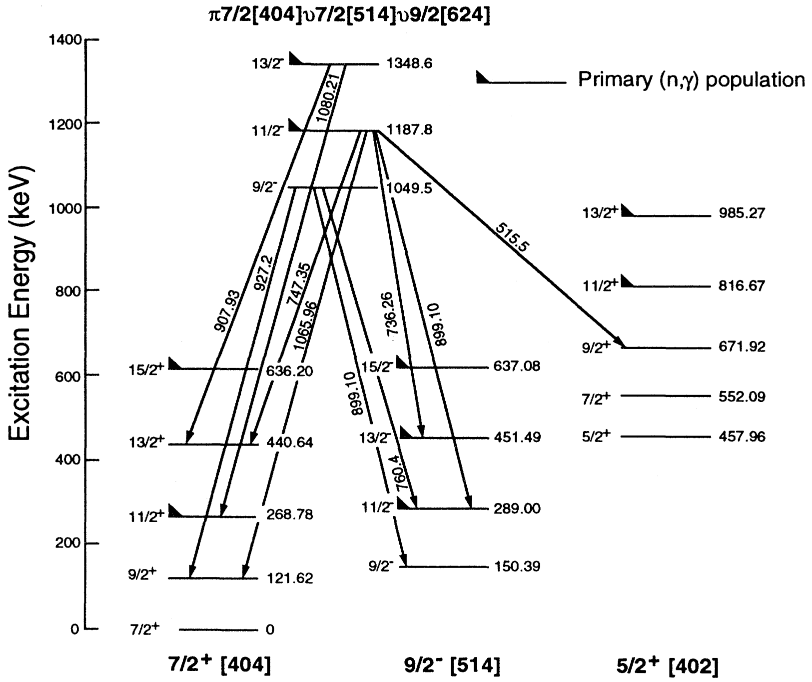

FIG. 2. The newly proposed $K=9/2^-$ band arising from the configuration $\pi 7/2[404]\nu 7/2[514]\nu 9/2[624]$. Primary (n,γ) decay is shown with a flag to the left-hand side of the levels. Depopulation of the levels of this three-quasiparticle band to various one-quasiparticle states is shown with arrows and the corresponding energies of the gamma transitions.

$\pi 7/2[404]\nu 7/2[514]\nu 3/2[512]$. We know that the $11/2^+$ member of this configuration has the complex nature indicated because the gamma decay is clearly connected to the one-quasiparticle, 7/2[404] proton state. This implies that it is the $K+2$ gamma vibration built on the ground state. However, since the band is populated in the (d,p) reaction with cross sections which imply stripping into the 3/2[512] neutron state, with about half the intensity expected [8], we are able to make the complex assignment shown in Table I.

The last two three-quasiparticle configurations in ^{177}Lu both correspond to stripping into the 1/2[510] and

TABLE I. Three-quasiparticle configurations and corresponding bands in ^{177}Lu.

Configuration	K^π values of the 4 expected bands	Observed K^π values	Energy in keV of observed bandheads	Band structure, J^π
$\pi 7/2[404]\nu 7/2[514]\nu 9/2[624]$	$23/2^-$	$23/2^-$	970.17	$23/2^-$, $25/2^-$
	$9/2^-$	$9/2^-$	1049.5	$9/2^-$, $11/2^-$, $13/2^-$
	$5/2^-$			
	$5/2^-$			
$\pi 9/2[514]\nu 7/2[514]\nu 9/2[624]$	$25/2^+$			
	$11/2^+$	$11/2^+$	1230.61	only bandhead observed
	$7/2^+$	$7/2^+$	1241.4	only bandhead observed
	$7/2^+$	$7/2^+$	1337.1	only bandhead observed
$\sim 50\%$ $\pi 7/2[404]\otimes(K+2)_\gamma+\sim 50\%$ $\pi 7/2[404]\nu 7/2[514]\nu 3/2[512]$	$17/2^+$			
	$11/2^+$	$11/2^+$	1305.2	$11/2^+$, $13/2^+$
	$3/2^+$			
	$3/2^+$			
$\pi 7/2[404]\nu 7/2[514]\nu 1/2[510]$	$15/2^+$	$15/2^+$	1356.93	$15/2^+$, $17/2^+$, $19/2^+$
	$13/2^+$	$13/2^+$	1453.95	$13/2^+$, $15/2^+$, $17/2^+$
	$1/2^+$			
	$1/2^+$			
$\pi 7/2[404]\nu 7/2[514]\nu 1/2[521]$	$15/2^+$	$15/2^+$	1632.68	$15/2^+$, $17/2^+$
	$13/2^+$	$13/2^+$	1453.95	$13/2^+$, $15/2^+$, $17/2^+$
	$1/2^+$			
	$1/2^+$			

1/2[521] neutron states. They are very clearly observed in the (d,p) reaction, and their cross section and "fingerprint patterns" make this assignment quite strong [8].

III. STUDY OF POSSIBLE ΔK FORBIDDENNESS IN THE DECAY OF NEUTRON RESONANCES IN ^{177}Lu

It has been known for a long time (see, for example, Ref. [22]) that in the low-energy regime, gamma transition rates are influenced by the K values of the two bands involved in the transition. Specifically, a gamma transition is ΔK forbidden if $\Delta K = \mid K_i - K_f \mid$ is greater than λ, the multipolarity of the transition. It has been suggested that the transition rate is reduced [22] by the factor $10^{2(\Delta K - \lambda)}$.

The question then naturally arises—how high in the energy spectrum is the K value of the band a good quantum number, leading to ΔK forbiddenness in gamma transitions to the low-energy part of the spectrum?

One way to test this question experimentally is to look at the gamma decay of neutron capture resonances. In our example, we consider the thermal neutron capture into the $K^\pi = 7^-$ ground state of ^{176}Lu leading to the capture states $K^\pi = 13/2^-$ and $15/2^-$ in ^{177}Lu, assuming only neutron capture. The subsequent dipole decay from these states can then test whether or not the K quantum number is still effective. If it is effective, one will expect that dipole transitions to states with K values less than 11/2 should be more forbidden than dipole transitions to K values of 11/2, 13/2, 15/2, and 17/2.

Primary gamma transitions following neutron capture in ^{176}Lu have been measured in two studies [8,10] and reported in Nuclear Data Sheets [20]. There is good overall agreement between these two studies. However, we use the combined listing of Ref. [20], which is mostly that of Ref. [10], because of its higher resolution and lower background.

In order to make a comparison between the various primary transitions following neutron capture, it is necessary to make a correction for the energy dependence of the gamma transitions. We have assumed an E_γ^5 dependence as specifically suggested in Refs. [23–25]. While it is clear that there can be some uncertainty in the choice of this exponent, the result is not very dependent on this choice [1].

In Table II the primary gamma transitions are listed, together with the K, I^π and the energy of the levels populated, the intensities of the gamma transitions, and the intensities corrected by the E_γ^5 gamma dependence. Based on the assigned K, I^π values the primary gamma transitions are then assumed to be allowed or forbidden, as indicated in Table II.

A number of points concerning Table II and its analysis need to be made.

The unobserved lines have been included in Table II when it has been possible to estimate an upper limit of the intensity by inspection of the spectra displayed in Ref. [10].

The levels at 1303.1 and 1305.2 keV appear as a doublet in the data of Michaud *et al.*, but are resolved in the table of Minor *et al.* We have therefore used the intensities and γ energies tabulated by Minor *et al.* (3.8, 5770.3 keV and 1.0, 5766 keV, respectively).

It is immediately obvious that the highest values of the energy-corrected intensities occur for allowed transitions. However, it is necessary to take into account all transitions and to compare the intensities for all allowed and all forbidden transitions. Two different methods for analyzing the data are used.

A straightforward but somewhat crude way of doing this is by summing the energy-corrected intensities for all forbidden transitions and dividing by their number, and then doing the same for the allowed transitions. The results are

$$\frac{\Sigma_F}{n_F} = \frac{28.82}{21} = 1.37 \text{ photons}/10^7 \text{ neutron captures/MeV}^5 ,$$
$$\frac{\Sigma_A}{n_A} = \frac{71.35}{13} = 5.49 \text{ photons}/10^7 \text{ neutron captures/MeV}^5 ,$$

which gives a ratio between forbidden and allowed transition intensities of 0.25.

If we exclude the two tentative transitions, shown with superscript d in Table II, the result for the forbidden transitions differs slightly. It is

$$\frac{\Sigma_F}{n_F} = \frac{26.63}{19} = 1.40 \text{ photons}/10^7 \text{ neutron captures/MeV}^5 ,$$

which gives a ratio between forbidden and allowed transition intensities of 0.26.

An advantage of this straightforward method is that doublets where both transitions are either forbidden or allowed can be successfully used. Hence, the doublet at 6436.1 keV has been included in the above calculations, since it does not matter what the ratio of intensities is in populating the 636.2 and 637.1 keV states. Furthermore, all primary transitions are compared in this straightforward method.

A second and more reliable way of analyzing this problem is described in Ref. [2]. This method takes into account that the transition intensities depend on the spin and parity of the final state, and therefore compares transitions only within the same spin and parity group. For each transition, the relative intensity $x_i = I_i(J,\pi)/\langle I(J,\pi)\rangle$, where $\langle I(J,\pi)\rangle$ is the average energy-corrected intensity measured for final states of the relevant spin and parity. For the procedure to be valid, the average must include both allowed and forbidden transitions. After this approximate elimination of the spin-parity dependence in the transition probabilities, the relative intensities x_i from different spin-parity groups can be compiled into one forbidden and one allowed ensemble. The average x values for the two ensembles are found to be

$$\langle x\rangle_F = 0.59 \text{ and } \langle x\rangle_A = 1.31$$

which gives a ratio between forbidden and allowed transition intensities of 0.45. This number agrees excellently with the systematics found for ^{168}Er, ^{178}Hf, and ^{166}Ho

(Refs. [1,2,26]).

This method necessitates a more careful treatment of doublets, and in earlier works [2,26] we have developed the following standard prescription: If the two levels have opposite parities, we subtract the average energy-corrected intensity $\langle I(J,\pi)\rangle$ for the group of final states having the same J^π as the $M1$-populated level (if such an average is available) from the total energy-corrected intensity of the doublet transition. We then assign the remaining energy-corrected intensity to the $E1$-populated level. In this case the $M1$ populated level has $J^\pi = 15/2^-$. We have no reliable average intensity for the $15/2^-$ group, since the intensity of the 5508.5 keV transition can only be given an upper limit. Hence, we have omitted the doublet from the second method of analysis.

In the present ensemble there are only forbidden transitions to states with negative parity and consequently there are no allowed transitions with which to compare the intensities. These transitions are therefore excluded. This exclusion is the main reason why the first straightforward approach gives a more pronounced K dependence than the more reliable method of Ref. [2]. The fact that all the $M1$ transitions are in the forbidden group may partially explain why the ΔK forbiddeness is smaller using the more reliable method.

It should also be noted that we used the intensity upper limits of all transitions expected, but not observed. Since

TABLE II. Primary dipole gamma transitions observed or expected following neutron capture in the 7^- state of ^{176}Lu into various low-lying states in ^{177}Lu. In the fifth column the primary gamma intensities are corrected by an E_γ^5 energy factor.

K, I^π	Level (keV)[a]	Primary γ[b]	I_γ $\gamma/10^3$ n cap[b]	$\frac{I_\gamma/10^7\ n\ \mathrm{cap}}{E_\gamma^5(\mathrm{MeV})}$	ΔK forbidden or allowed
$7/2, 11/2^+$	268.8	6803.6	10.7	7.44	forbidden
$9/2, 11/2^-$	289.0	6782.4	0.2	0.14	forbidden
$7/2, 13/2^+$	440.6	6631.80	$\leq$0.20	$\leq$0.16	forbidden
$9/2, 13/2^-$	451.5	6621.3	0.5	0.39	forbidden
$7/2, 15/2^+$	636.2	{6436.1[c]	2.9[c]	{2.63[c]	forbidden
$9/2, 15/2^-$	637.1				forbidden
$5/2, 11/2^+$	816.7	6255.7	1.9	1.98	forbidden
$9/2, 17/2^-$	844.9	6227.50	$\leq$0.20	$\leq$0.21	forbidden
$7/2, 17/2^+$	854.3	6218.10	$\leq$0.20	$\leq$0.22	forbidden
$1/2, 13/2^-$	957.3	6115.10	$\leq$0.20	$\leq$0.23	forbidden
$1/2, 11/2^+$	980.2	6092.6	1.1	1.31	forbidden
$5/2, 13/2^+$	985.3	6086.4	0.5	0.60	forbidden
$5/2, 15/2^+$	1176.8	5895.9	2.1	2.95	forbidden
$(9/2,11/2^-)$[d]	1187.8	5884.0	0.4	0.57	forbidden
$1/2, 17/2^-$	1201.6	5870.80	$\leq$0.20	$\leq$0.29	forbidden
$11/2, 11/2^+$	1230.6	5841.9	1.0	1.47	allowed
$1/2, 11/2^-$	1286.9	5786.0	0.7	1.08	forbidden
$1/2, 13/2^+$	1303.1	5770.3	3.8	5.94	forbidden
$11/2, 11/2^+$	1305.2	5766.0	1.00	1.57	allowed
$1/2, 15/2^+$	1344.8	5726.60	$\leq$0.20	$\leq$0.33	forbidden
$(9/2,13/2^-)$[d]	1348.6	5724.2	1.0	1.62	forbidden
$15/2, 15/2^+$	1356.9	5716.2	1.8	2.96	allowed
$5/2, 17/2^+$	1389.6	5682.80	$\leq$0.20	$\leq$0.34	forbidden
$13/2, 13/2^+$	1453.9	5617.9	0.7	1.25	allowed
$11/2, 13/2^+$	1471.3	5601.8	8.0	14.50	allowed
$13/2, 13/2^+$	1502.6	5570.5	9.1	16.96	allowed
$15/2, 17/2^+$	1544.1	5527.0	0.6	1.16	allowed
$1/2, 15/2^-$	1563.9	5508.50	$\leq$0.20	$\leq$0.39	forbidden
$13/2, 15/2^+$	1607.5	5465.6	5.6	11.48	allowed
$15/2, 15/2^+$	1632.7	5439.2	1.5	3.15	allowed
$13/2, 15/2^+$	1677.90	5395.7	2.8	6.12	allowed
$13/2, 17/2^+$	1786.3	5286.10	$\leq$0.20	$\leq$0.48	allowed
$15/2, 17/2^+$	1812.6	5258.2	0.5	1.24	allowed
$13/2, 17/2^+$	1880.1	5192.2	3.4	9.01	allowed

[a] Level energies from E. Browne, Nucl. Data Sheets **68**, 747 (1993), to the nearest 0.1 keV, except where more accurate values are available from the literature.

[b] Primary γ energies and intensities are from B. Michaud, J. Kern, L. Ribordy, and L.A. Schaller, Helv. Phys. Acta **45**, 931 (1972).

[c] A single primary gamma transition was observed populating both the 636.2 and 637.1 keV states; it was not used in the second more reliable method of analyzing the data.

[d] New assignment; see text and Fig. 2.

eight out of nine of these are ΔK-forbidden transitions, if the actual intensities were known the ratio between forbidden and allowed transitions would be smaller.

IV. CONCLUSION

As observed in the case of neutron resonances produced by the capture of thermal neutrons on odd-A, odd-N systems [1,2] and on an odd-A, odd-Z system [26], this test of forbiddenness involving an odd-odd target which neutron captures to the fairly high-spin resonance states of $13/2^-$ and $15/2^-$ shows a distinct ΔK forbiddenness.

We have not assumed any K mixing which will certainly occur. However, the effect of K mixing would be to decrease ΔK forbiddenness to the present considerable values. While there should be some p-wave capture by the thermal neutron beams, this effect would be very small as implied by the good agreement between the experimental intensities of Refs. [8] and [10] with different thermal neutron beams. ΔK forbiddenness is particularly interesting since the allowed transitions all involve transitions to three-quasiparticle bands, whereas the forbidden transitions all involve one-quasiparticle bands. The possibility of using this three-quasiparticle, one-quasiparticle nature as the origin of the two intensity groups cannot be excluded. However, in all cases studied thus far (^{166}Ho, ^{168}Er, and ^{178}Hf) there is evidence for K forbiddenness of the primary gamma transitions from neutron capture states. Therefore it seems unlikely that the three-quasiparticle, one-quasiparticle nature of the two intensity groups is the correct explanation. In the case of ^{177}Lu the energy of the capture state is quite high, namely 7072.4 keV. The significance of this in terms of the amount of mixing in these relatively high energy capture states, the degree of chaos, or the possibility that the capture proceeds via unique mechanisms must still be determined.

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