K dependence in the γ decay of neutron resonances in ^{166}Ho

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

R. K. Sheline
Florida State University, Tallahassee, Florida 32306

(Received 1 November 1993)

The energy-corrected intensities of the primary γ transitions in ^{166}Ho following thermal and average resonance neutron capture are calculated from data available in the literature. The γ decay of this odd-odd nucleus shows the same K dependence as earlier seen in the even-even nuclei ^{168}Er and ^{178}Hf.

PACS number(s): 23.20.Lv, 05.45.+b, 25.40.Lw, 27.70.+q

In a recent study [1] of ^{168}Er and ^{178}Hf the intensities of primary γ-ray transitions from neutron resonance states to low-lying states with known K quantum numbers were analyzed. The conclusion was that the capture states had to be assigned K quantum numbers in order to explain the observed γ-ray intensity distribution. If one assumes that the capture states have good K values, it was found that the average transition rates to states which are forbidden according to normal K selection rules were significantly lower than for K-allowed transitions. This was interpreted as a possible K hindrance, which implies that the K quantum number still has some meaning in the resonance region. The result is in conflict with the common opinion that states in this energy region have a completely chaotic quantal structure [2].

When this possible K hindrance was first published [3] it met significant opposition. Barrett *et al.* [4] argued that the results were in conflict with the statistical model, and after reexamining the tabulated data, they claimed that our results were not in agreement with these data. As a consequence of this criticism, we went through a new detailed analysis which still maintained a significant K dependence in the γ decay [1].

In this work the reported decay properties of ^{166}Ho after both thermal and average resonance neutron capture [5–9] have been investigated. The fact that ^{166}Ho is an odd-odd nucleus introduces new aspects compared to the even-even ^{168}Er and ^{178}Hf nuclei. Because of the strong pairing effect, most of the states in the low-energy region of the even-even system are vibrational states or two-quasiparticle states with significant correlations. In the odd-odd system the lowest regime is characterized by two-quasiparticle states which produce blocking of both the neutron and the proton orbitals. This results in a significant reduction of the pair correlations for both particle types. In addition, the capture states in odd-odd systems lie about 1.5 MeV lower than in even-even systems. Hence, it is interesting to see whether there are any differences between odd-odd and even-even nuclei with regard to K dependence in the γ decay.

Below, a short review of the method of analysis is given. A more detailed description is given in Ref. [1]. The ground state of the target nucleus ^{165}Ho has K^π equal to $\frac{7}{2}^-$. The spin of the capture states are therefore restricted to 3 and 4 due to the dominance of s-wave capture. According to usual spin selection rules, all states with spin $J = 2 - 5$ are then, in principle, accessible through direct dipole transitions.

If K is still a good quantum number in the resonance region, the capture states will have a K value equal to 3 or 4, and transitions to states with $K = 0, 1$ should be hindered. In the following, transitions to states with $K = 0, 1$ are called forbidden, and those to states with $K = 2$–5 are called allowed, in accordance with the procedure described in Ref. [1].

In order to compare the transition rates, it is necessary to correct for the γ-energy dependence. This is done by dividing the intensity of each transition by E_γ^5. There might be some dispute about the exponent of 5, but the results are not very dependent on the exact value of this parameter [3].

The transition probability also depends on the spin and parity of the final state. Without detailed knowledge about the structure of both states involved in the transition, this spin dependence is difficult to predict. We therefore determined the average energy-corrected intensity, $\langle I(J,\pi)\rangle$, for each group of final states with the same spin and parity. Finally, the energy-corrected intensity of each individual transition is represented by the ratio

$$x_i = I_i(J,\pi)/\langle I(J,\pi)\rangle \ . \tag{1}$$

A possible K dependence should now be revealed in the distribution of x values obtained for the forbidden and allowed transitions, respectively. One may introduce an empirical "hindrance factor" as the ratio $\langle x\rangle_F/\langle x\rangle_A$ of the centroids of the two distributions.

According to the literature, there is some dispute about the assignments of some of the levels in ^{166}Ho. Therefore the analysis has been done first by using the assignments reported in Ref. [7] with the addition of the new bands assigned in Ref. [8], see Table I. It is then redone using the assignments of Ref. [9], see Table II. Level schemes including all $J = 2$–5 levels with known K values are shown in Figs. 1 and 2 for the two sets of assignments, respectively.

When using the assignments of Ref. [9], there are only forbidden transitions to 3^- and 5^- states, and consequently there are no allowed transitions with which to

compare the intensities. These transitions are therefore excluded. For the same reason transitions to 3^-, 4^-, and 5^- states are excluded when the assignments of Refs. [7,8] were used. Transitions to levels with no reported intensities are also excluded.

In order to decide whether a transition is forbidden or allowed, the K quantum number of the final state must be well established. The 3^+ level at 593 keV, the 4^+ level at 672 keV, and the 5^+ level at 770 keV have uncertain K values and are therefore excluded before the x values are calculated. They are, however, used when the average intensities $\langle I(J,\pi)\rangle$ of transitions to the respective spin and parity groups are calculated.

It is also necessary to exclude transitions due to Coriolis coupling. Even a small admixture of $K \geq 2$ components in the final states with K equal to 0 or 1 may influence the transition probabilities to these states. On the other hand, admixtures of low K values in the states with $K \geq 2$ reduce the transition probability by only a small factor. Transitions to obviously perturbed states with $K = 0, 1$ have therefore been excluded.

In order to decide which levels to exclude, the experimental Routhians [10] versus rotational frequency have been investigated. The Routhians depend on the alignment of the spin along the rotational axis. Usually the Coriolis coupling to other bands is different for the two signatures of the band, giving rise to so-called signature splitting. The Routhian with the highest average K value is less favored in energy. According to this analysis, the 3^- and 5^- members of 3 bands have admixtures of higher K values. However, these states have already been removed in our analysis because there are no allowed transitions to 3^- and 5^- states. No levels are therefore excluded due to Coriolis coupling.

The energy-corrected intensities and the x values of the transitions to the various levels are shown in Tables I and II for the two sets of assignments, respectively. The

TABLE I. Energy-corrected intensities and x values of transitions to levels with known K values. The assignments are taken from Refs. [7,8].

Final state		Thermal n capture		ARC	
E_x(keV)	$I^\pi K$	I_γ/E_γ^5	x	I_γ/E_γ^5	x
54	2^-0	1.00	0.18	1.00	0.88
171	3^-0	11.55		1.84	
180	4^-0	2.59		2.38	
191	3^+3	69.70	2.05	10.85	1.18
261	4^+3	27.84	0.88	11.15	1.17
264	5^+5	no		3.76	0.64
330	5^-0	1.26		0.97	
348	5^+3	1.70	0.11	6.20	1.06
372	4^+4	80.70	2.54	12.58	1.32
390	2^-1	no		no	
416	2^-1	5.63	1.00	0.92	0.80
430	2^+2	213.37	2.89	7.44	1.39
465	2^+1	6.81	0.09	3.66	0.68
469	3^-1	no		no	
471	5^+4	34.00	2.20	6.85	1.17
476	3^-1	29.40		1.82	
482	3^+2	53.16	1.57	7.66	0.83
522	3^+1	9.38	0.28	9.27	1.01
543	4^-1	8.30		0.96	
544	4^-1				
548	4^+2	10.86	0.34	8.11	0.85
559	4^+4	48.69	1.53	9.35	0.98
563	2^-2	10.24	1.82	1.50	1.32
593	$3^+(3)$	26.53		10.12	
595	2^-0	no		no	
598	4^+1	19.27	0.61	10.32	1.09
605	2^+1	1.33	0.01	4.98	0.93
628	5^-1	1.36		0.60	
634	5^+2	2.18	0.14	7.26	1.24
662	3^+1	10.90	0.32	8.21	0.89
672	$4^+(3)$	no		6.89	
682	5^-1	no		no	
693	5^+1	18.68	1.23	6.05	1.04
724	3^-0	1.18		0.52	
736	4^+1	3.28	0.10	8.15	0.86
758	4^-0	no		no	
770	$5^+(3)$	19.10		4.87	
832	5^+1	18.27	1.11	5.87	1.01
926	5^-0	1.07		2.22	

TABLE II. Energy-corrected intensities and x values of transitions to levels with known K values. The assigments are taken from Ref. [9].

Final state		Thermal n capture		ARC	
E_x(keV)	$I^\pi K$	I_γ/E_γ^5	x	I_γ/E_γ^5	x
54	2^-0	1.00	0.20	1.00	1.04
171	3^-0	11.55		1.84	
180	4^-0	2.59	0.30	2.37	1.30
191	3^+3	69.70	2.05	10.85	1.17
261	4^+3	27.84	0.91	11.14	1.18
264	5^+5	no		3.75	0.64
330	5^-0	1.26		0.97	
348	5^+3	1.70	0.11	6.19	1.06
372	4^+4	80.70	2.63	12.57	1.34
416	2^-1	5.63	1.13	0.91	0.95
430	2^+2	213.37	2.89	7.44	1.38
465	2^+1	6.81	0.09	3.65	0.68
471	5^+4	34.00	2.56	6.85	1.18
476	3^-1	29.40		1.82	
482	3^+2	53.16	1.57	7.66	0.83
522	3^+1	9.38	0.28	9.27	1.00
544	2^-2	8.30	1.67	0.95	0.99
548	4^+2	10.86	0.35	8.10	0.86
563	4^-1	10.24	1.19	1.50	0.82
593	$3^+(3)$	26.53		10.11	
597	3^-2	19.27		10.32	
598	4^+1				
605	2^+1	1.33	0.02	4.97	0.92
634	5^+2	2.18	0.14	7.25	1.25
658	5^-1	9.75		1.04	
662	3^+1	10.90	0.32	8.21	0.89
668	4^-2	12.92	1.51	1.60	0.87
672	$4^+(3)$	no		6.89	
736	4^+1	3.29	0.11	8.14	0.86
758	5^-2	no		no	
770	$5^+(3)$	19.10		4.87	
832	5^+1	18.27	1.21	5.87	1.01

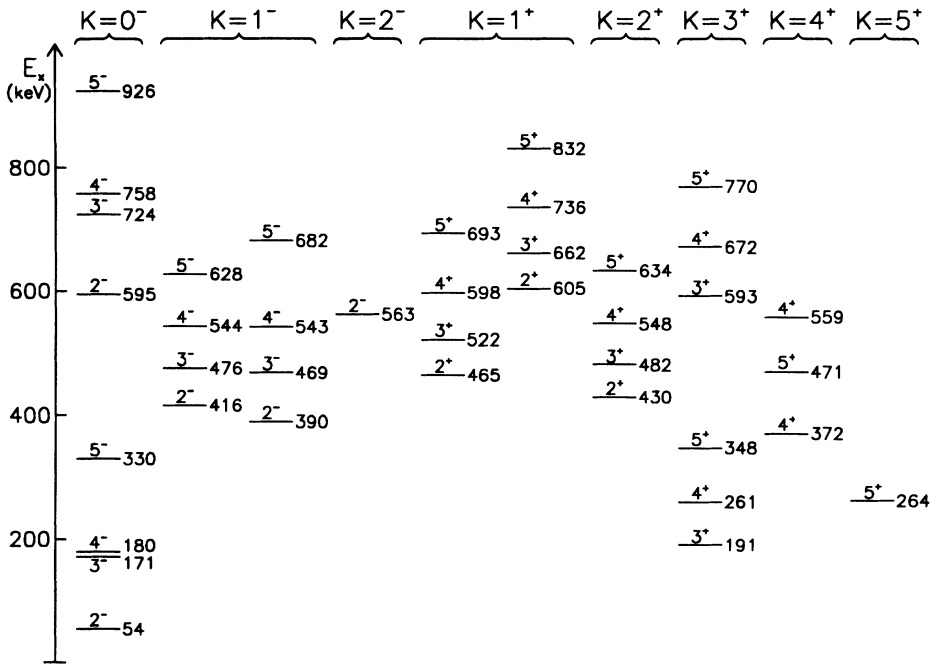

FIG. 1. Level scheme of ^{166}Ho based on assignments taken from Refs. [7,8].

transitions that are excluded for some of the reasons discussed above are tabulated without x value. The intensity distributions of the forbidden and allowed transitions are shown in Fig. 3. In Table III the average energy-corrected intensities for forbidden $\langle x \rangle_F$ and allowed $\langle x \rangle_A$ transitions and the ratio $\langle x \rangle_F / \langle x \rangle_A$ are listed.

For the thermal neutron data, the ratio of forbidden-to-allowed transition intensities is 0.33, regardless of whether the assignments of Refs. [7,8] or Ref. [9] are used. In ^{168}Er and ^{178}Hf this ratio is 0.54 [1], thus the K dependence is even more pronounced in ^{166}Ho.

The ARC data are not very sensitive to which set of assignments are used either. The ratio of forbidden-to-allowed transition intensities is 0.84 and 0.89 for the assignments of Refs. [7,8] and Ref. [9], respectively. The result obtained for the ARC data in ^{168}Er and ^{178}Hf is 0.84; see Ref. [1].

It is essential to investigate the stability of the ^{166}Hf results with respect to possible variations in the level scheme. Hence we have analyzed the consequences of including doublets and tentative level assignments. A prescription for analyzing doublets was developed in Ref. [1]. When the doublet consists of two states with opposite parity, the mean energy-corrected intensity of the M1 transitions to states of the spin of interest is subtracted from the total intensity of the doublet. The difference in

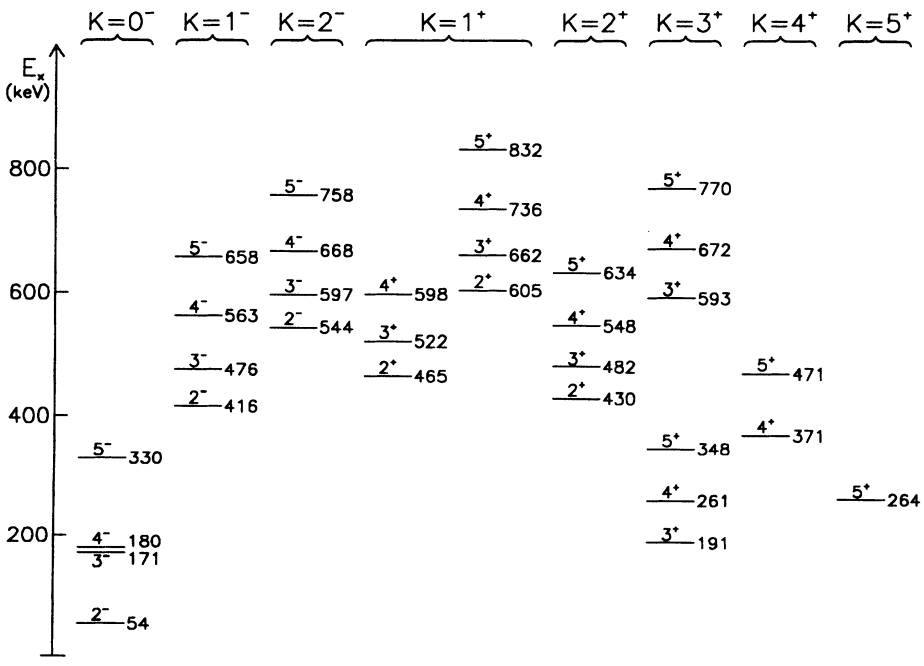

FIG. 2. Level scheme of ^{166}Ho based on assignments taken from Ref. [9].

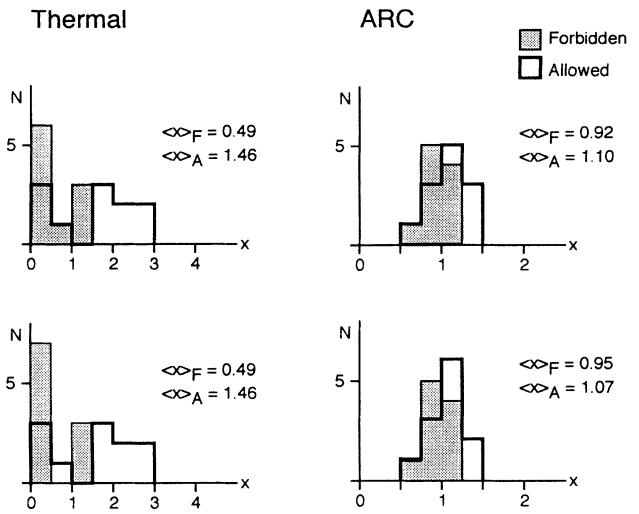

FIG. 3. The number of transitions as a function of the relative energy-corrected intensity x. The assignments of [7,8] and [9] are used in the upper and lower part of the figure, respectively.

intensity is assigned to the E1 transition. This method is justified by the fact that the E1 intensity is on the average five times larger than the M1 intensity. It is considered to be particularly reliable when applied to the ARC data.

The only doublet in the present data set is the 5645 keV peak, which according to the assignments of Ref. [9] consists of transitions to both the $J^\pi K = 3^-2$ and 4^+1 states. This transition has been excluded so far, but the effect of including it has been tested in order to check the sensitivity of the data. Using the prescription of Ref. [1], the ratio of forbidden-to-allowed transitions is reduced from 0.33 to 0.30 in the thermal neutron case, while there is no effect in the ARC case.

Recently, Balodis [11] presented 17 new assignments of relevance for the present analysis, in addition to those given by Ref. [9]. Although these assignments must at present be considered to be tentative, we have investigated the effect on the ratio between forbidden and allowed transitions. One particular assignment requires specific comment. Balodis [11] suggests a new $J^\pi K = 5^-5$ level at 431 keV, which together with the $J^\pi K = 2^+2$ at 430 keV forms a doublet. According to our method of analyzing doublets described above, the average intensity of the 5^--states is subtracted from the total intensity, and the difference in intensity is assigned to the $J^\pi K = 2^+2$ state. According to the analysis described above, the 3^- and 5^- members of the ground band should be excluded due to Coriolis coupling. However, these exclusions do not change the ratio of forbidden-to-allowed transition rates.

TABLE III. The number of forbidden N_F and allowed N_A transitions, the average energy-corrected intensities for forbidden $\langle x\rangle_F$ and allowed $\langle x\rangle_A$ transitions, and the ratio $\langle x\rangle_F/\langle x\rangle_A$ for the thermal neutron and the ARC data and for the two different sets of assignments.

	N_F	N_A	$\langle x\rangle_F$	$\langle x\rangle_A$	$\langle x\rangle_F/\langle x\rangle_A$
Thermal [7,8]	10	11	0.49	1.46	0.33
ARC [7,8]	10	12	0.92	1.10	0.84
Thermal [9]	10	11	0.49	1.46	0.33
ARC [9]	10	12	0.95	1.07	0.89

For the thermal neutron data, the averaged energy-corrected intensities of the forbidden and allowed transitions now become $\langle x\rangle_F = 0.68$ and $\langle x\rangle_A = 1.27$, respectively. This gives a ratio of $\langle x\rangle_F/\langle x\rangle_A = 0.54$.

Applied to the ARC data, these new assignments give averaged energy-corrected intensities of $\langle x\rangle_F = 0.97$ and $\langle x\rangle_A = 1.00$ for the forbidden and allowed transitions, respectively. This gives a ratio of $\langle x\rangle_F/\langle x\rangle_A = 0.97$. Hence the effect seems to vanish in the ARC data combined with the level scheme of Ref. [11].

In conclusion, the gamma decay of ^{166}Ho after thermal neutron capture shows a significant suppression of so-called K-forbidden primary transitions. These new findings are consistent with the ^{168}Er and ^{178}Hf data, and demonstrate that the apparent K-hindrance effect is present in odd-odd as well as even-even nuclei.

The difference between the results for thermal and ARC neutron energies remains unexplained so far. This discrepancy gives rise to some uncertainty with respect to a direct causal connection between the observed correlation and a conserved K quantum number for the capture state. In order to illuminate the structural or dynamical mechanisms responsible for the phenomenon, it is important to understand why the effect is attenuated in the ARC data.

Financial support from the Norwegian Research Council is acknowledged. One of us (R.K.S.) wishes to acknowledge the support of the National Science Foundation under Contract PHY92-07336.

[1] J. Rekstad, T. S. Tveter, M. Guttormsen, and L. Bergholt, Phys. Rev. C **47**, 2621 (1993).
[2] O. Bohigas, M. J. Giannoni, and C. Schmit, Phys. Rev. Lett. **52**, 1 (1984).
[3] J. Rekstad, T. S. Tveter, and M. Guttormsen, Phys. Rev. Lett. **65**, 2122 (1990).
[4] B. B. Barrett, R. F. Casten, J. N. Ginocchio, T. Seligman, and H. A. Weidenmüller, Phys. Rev. **45**, R1417 (1992).
[5] T. J. Kennett, M. A. Islam, and W. V. Prestwich, Phys. Rev. C **30**, 1840 (1984).
[6] L. M. Bollinger and G. E. Thomas, Phys. Rev. C **2**, 1951 (1970).
[7] A. Ignatochkin, E. Shurshikov, and Yu. Jaborov, Nucl. Data Sheets **52**, 365 (1987).
[8] R. K. Sheline and P. C. Sood, Phys. Rev. C **40**, 1065 (1989).
[9] E. Shurshikov and N. V. Timofeeva, Nucl. Data Sheets **67**, 45 (1992).
[10] R. Bengtson and S. Frauendorf, Nucl. Phys. **A442**, 139 (1985).
[11] M. Balodis, in Proceedings of the Conference on Capture γ-Ray Spectroscopy and Related Topics, Fribourg, Switzerland, 1993 (unpublished); private communications.

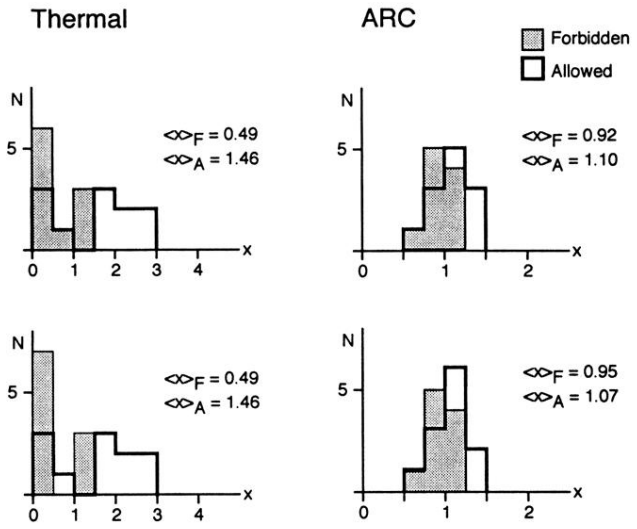

FIG. 3. The number of transitions as a function of the relative energy-corrected intensity x. The assignments of [7,8] and [9] are used in the upper and lower part of the figure, respectively.