Chaos in Nuclei and the K Quantum Number

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The intensities of γ transitions from neutron-resonance states in ^{168}Er and ^{178}Hf to low-lying states with spin 2–5 are shown to depend on the K values of the final states. This K dependence favors a conclusion that the resonance states can also be associated with good K quantum numbers. The result contradicts the hypothesis that K is completely mixed in this energy region as expected for a chaotic structure.

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Studies of neutron and proton resonances have revealed a convincing agreement between the resonance statistics and the predictions of random-matrix methods initiated by Wigner and developed mainly by Dyson and Mehta.[1] In particular, the Gaussian-orthogonal-ensemble (GOE) method[2] has been successful in describing the nuclear data, and leaves an impression of the nuclear resonance states as completely mixed and very complex states. This result is in contrast to the expectations of a Poisson-type distribution of resonance energies and widths in a system with independent degrees of freedom.[3]

The similarity between the nuclear resonances and the results obtained for very simple chaotic classical systems, e.g., the Sinai billiard, suggests that the nucleus has a more or less complete quantal chaotic structure at the excitation energy where these resonances occur.[3]

Further progress in the study of chaotic phenomena demands more quantitative information about the quantal properties of individual states in the chaotic regime. In a regime of complete chaos most of the quantum numbers which determine the nuclear structure in the ground-state region are expected to vanish. Hence, the degree to which these quantum numbers are mixed is a possible measure of the amount of disorder in the system.

A particularly interesting quantum number in this respect is the projection K of the total spin along the symmetry axis in deformed nuclei. The widths of resonance states populated by thermal neutron capture in nuclei with high ground-state spin (and spin projection K) agree with a single Porter-Thomas distribution, as expected in the case of complete K mixing.[4,5] In the opposite case, good K quantum numbers should imply both allowed and forbidden transitions, and the usual hindrance factor of approximately 10 associated with the latter would give rise to an additional Porter-Thomas distribution corresponding to smaller neutron widths. Hence, these investigations support the conclusion that the K mixing is complete as in a chaotic regime.

In this Letter we report on an investigation of the decay properties of the neutron resonances in ^{168}Er and ^{178}Hf. Precise experiments[6,7] give an opportunity to study in detail the γ decay of the resonance states to low-lying states with well-known properties. The target nuclei ^{167}Er and ^{177}Hf have K^π equal to $\frac{7}{2}^+$ and $\frac{7}{2}^-$, respectively. The energy spread of the absorbed neutrons is large compared to the average spacing between the resonances. Hence, a large number of resonances is populated, all with spin 3 or 4 and with opposite parities in the two nuclei due to the dominance of s-neutron capture.

The picture of a chaotic regime means a unique K quantum number cannot be assigned to these resonance states. In other words, the states are complex with a very large number of components of any K number permitted by the spin restrictions. The primary transitions from these states to low-lying states in the two nuclei have intensities which can be compared with the K number of the final states. Provided that the K mixing is complete, all K components are present in the resonance wave function in approximately equal portions, and the reduced intensity or transition probability is governed by spin and parity only.

On the other hand, if the K quantum number is fully or partly conserved after the neutron absorption, γ transitions to states with $K=0$ and 1 violate the K transition rule for dipole transitions and should be hindered. Consequently, we have two models to compare the experimental data with which hopefully will be conclusive with regard to the K properties of the resonance states.

The results of this comparison are shown in Fig. 1. All the possible transitions to states with energy less than 2.5 MeV and with spin from 2 to 5 reported in Refs. 6 and 7 are included. The transitions are either of $M1$ or $E1$ type, in the first case partly mixed with $E2$. All transitions ending up in states with the same spin and parity are used to define an average transition rate for this group of transitions. The energy dependence is compensated for by means of an E_γ^n factor. We have plotted the number of transitions as a function of reduced transition probability. The reduced transition probability for the individual transition is defined as

$$x = \frac{I/E_\gamma^n}{\langle I/E_\gamma^n \rangle}, \qquad (1)$$

where I is the measured intensity in Refs. 6 and 7, E_γ^n is

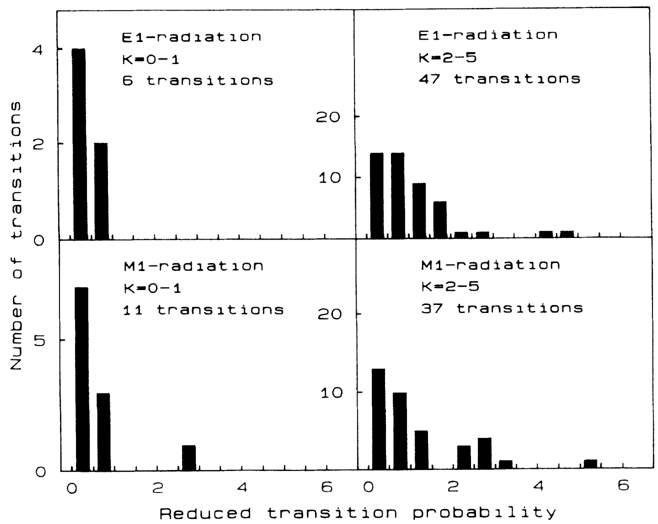

FIG. 1. Number of transitions vs reduced transition probability for $E1$ and $M1$ transitions to low-lying states with $K=0,1$ and $K=2$–5, respectively.

the energy correction factor, and $\langle I/E_\gamma^n \rangle$ the appropriate average reduced transition rate for the group of transitions that the actual transition belongs to. In accordance with Refs. 6 and 7, the value $n=5$ has been used.

In Fig. 1 the $E1$ and the $M1$ transitions are shown separately. Furthermore, the transitions have been divided according to the K quantum number of the final state. If the resonance states have good K value, transitions to $K=0$ and 1 states will be forbidden, while transitions to $K=3$ and 4 are allowed. Transitions to $K=2$ and 5 states are either forbidden or allowed, depending on whether the decaying resonance state has $K=3$ or 4.

It should be emphasized that only transitions to good K states have been included in the comparison. If the energy staggering of the band which the final state belongs to exceeds 5%, we assume that the Coriolis force is responsible for K mixing. Based on this criterion, 16 out of 114 transitions were excluded in the analysis.

It is evident from Fig. 1 that the K-forbidden and K-allowed transitions show different distributions. Although the number of transitions in the first group is low, these transitions are significantly less probable than the allowed ones. As seen in Fig. 2, both groups are consistent with the Porter-Thomas distribution

$$P(x)=C(x/\langle x\rangle)^{-1/2}\exp(-x/\langle x\rangle)\,, \qquad (2)$$

where x is the reduced transition probability. The average values of x are 0.41 ± 0.09 and 1.15 ± 0.09 for the two groups, respectively. Hence, it is fair to conclude that the K quantum number influences the transition probabilities.

In the analysis of the primary γ decay, we have made two assumptions: (i) The γ radiation shows an E_γ^n energy dependence with $n=5$. (ii) Transitions to final states

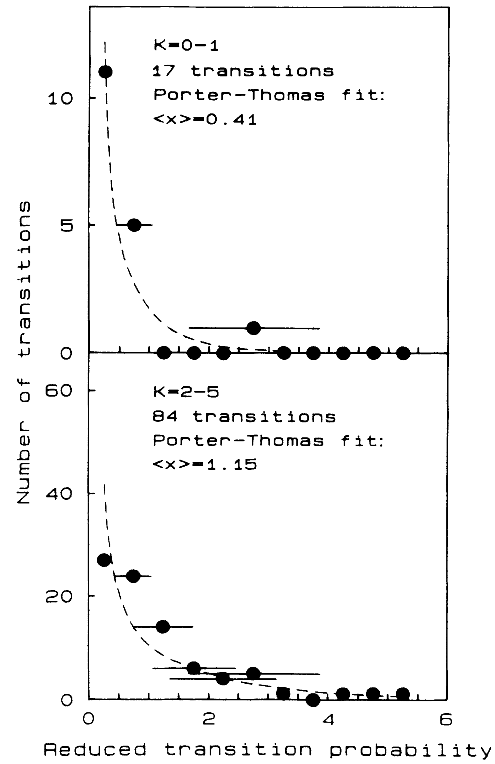

FIG. 2. Experimental probability distributions compared with Porter-Thomas distributions for K-forbidden and K-allowed transitions. The mean probabilities correspond to a hindance factor of 2.8 for transitions to $K=0,1$ states.

with $K=2$–5 have been classified as allowed. For test purposes, the average transition probabilities have also been computed with $n=3$ and with a more conservative definition of the group labeled allowed, including only transitions to states with $K=3$ and 4. The $\langle x\rangle$ values obtained are listed in Table I. It is evident that a change in these parameters does not alter significantly the ratio $\langle x\rangle_{\rm allowed}/\langle x\rangle_{\rm forbidden}$.

One question is whether some mechanism unrelated to the initial K distribution enhances the transitions to high-K final states. We have therefore also investigated the primary γ-decay pattern after neutron capture in target nuclei with K ranging from $\frac{1}{2}$ to $\frac{5}{2}$: ^{155,157}Gd,[8,9] ^{171,173}Yb,[10,11] and ^{183}W.[12] The average transition probabilities calculated as functions of K agree perfectly with the results expected for a system with partial K conserva-

TABLE I. Average transition probabilities $\langle x\rangle$ calculated for the various groups of transitions and for different values of the γ exponent n.

K values	$n=3$	$n=5$
0,1	0.49 ± 0.09	0.41 ± 0.09
2–5	1.15 ± 0.08	1.15 ± 0.08
3,4	1.19 ± 0.12	1.20 ± 0.12

tion. No trace has been revealed of any unknown mechanism channeling the γ strength into high-K levels.

The signature of the γ decay suggests that K is persisting in the original state, a result which contradicts the conclusion drawn from the study of resonance widths.[4,5] However, the present results are not necessarily in conflict with the data on resonance widths since we observe a hindrance factor of the order of 2–3 only. That hindrance is substantially smaller than the factor of 10 assumed for one time K-forbidden transitions and applied in the analysis of the resonance widths. The small factor found in the present study would probably be insufficient to distinguish between the two distributions of resonance widths.

Our conclusion is that nuclear states at an excitation energy of 8–8.5 MeV, produced in neutron capture, have vital K quantum numbers equal to those expected from the normal spin-coupling scheme for low-energy states. This contradicts the common opinion that states in this energy region are fully chaotic. The reduced hindrance factor may suggest a partial K admixture. That is not surprising when taking into account the very large density of states, and can be explained in terms of Coriolis coupling. The nucleus seems to be more resistant against breakdown of the regular orbital nucleonic structure than expected until now. An interesting question is the extent to which the complete mixing of the GOE model can be relaxed without disturbing the agreement with the resonance statistics.

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