NUMBER OF DEGREES OF FREEDOM IN PRIMARY γ-DECAY AFTER NEUTRON CAPTURE * **

T.S. TVETER[a], I. HUSEBY[a], L. BERGHOLT[a], M. GUTTORMSEN[a], E. MELBY[a], J. REKSTAD[a], S. SIEM[a] AND R.K. SHELINE[b]

[a]Department of Physics, University of Oslo, Box 1048 Blindern, N-0316 Oslo, Norway
[b]Departments of Chemistry and Physics, Florida State University, Tallahassee, Florida 32306, USA

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The intensities of primary γ-ray transitions following thermal and average resonance neutron capture have been found to depend on the final-state K quantum number. The apparent K-hindrance effect is significantly stronger in the thermal than in the ARC case. After thermal neutron capture, the shapes of the transition probability distributions indicate that the K-allowed transitions are associated with a higher number of degrees of freedom than the K-forbidden ones.

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In a series of recent papers, evidence has been presented for an apparent K hindrance effect in the primary γ-decay of states populated through thermal and average resonance neutron capture in deformed nuclei [1, 2].

The primary dipole γ-ray transitions into low-lying states with known quantum numbers have been studied for the following deformed nuclei: ^{168}Er, ^{174}Yb, ^{178}Hf (even-even), ^{166}Ho, ^{176}Lu, ^{182}Ta (odd-odd) and ^{177}Lu (odd-Z) [2, 3]. Dimensionless reduced relative transition probabilities x have been extracted by dividing out the dependence on γ-energy and final-state spin and parity in the measured transition probabilities. Hence the dependence on the final-state K quantum number is isolated, and the quantities x can be compiled into one K-forbidden ($K < K_{\mathrm{target}}-3/2$) and one K-allowed ($K_{\mathrm{target}}-3/2 \leq K \leq K_{\mathrm{target}}+3/2$) ensemble. Possible K selection

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effects in the decay pattern should then be revealed as different centroids and possibly different shapes for the x distributions obtained for the two groups of transitions. An empiric "hindrance factor" has been introduced, defined as the ratio $R = \frac{\langle x\rangle_F}{\langle x\rangle_A}$, where $\langle x\rangle_F$ and $\langle x\rangle_A$ are the average x values of the forbidden and allowed transitions, respectively. Technical details are explained in Ref. [1].

Results for the individual nuclei are listed in Table I. A noteworthy observation is that the K-hindrance is significantly stronger in thermal neutron capture than in ARC.

TABLE I

Average reduced relative transition probabilities $\langle x\rangle_F$ and $\langle x\rangle_A$ for forbidden and allowed transitions, respectively, and effective hindrance factors $R = \langle x\rangle_F/\langle x\rangle_A$. The numbers of transitions in the various ensembles are listed in parentheses. The uncertainties in R for all nuclei, R_{therm}=0.62 ± 0.11, and R_{ARC}=0.94 ± 0.09, are calculated as the standard deviation in the results of the individual nuclei.

Nucleus	K^{π}_{target}	$\langle x\rangle_F$ (therm)	$\langle x\rangle_A$ (therm)	R (therm)	$\langle x\rangle_F$ (2 keV)	$\langle x\rangle_A$ (2 keV)	R (2 keV)
^{168}Er	$7/2^+$	0.76 (18)	1.08 (48)	0.71	0.94 (17)	1.02 (30)	0.92
^{174}Yb	$5/2^-$	0.86 (7)	1.12 (8)	0.77	1.01 (7)	1.07 (8)	0.94
^{178}Hf	$7/2^-$	0.84 (15)	1.33 (9)	0.63	0.96 (14)	1.05 (10)	0.91
^{166}Ho	$7/2^-$	0.72 (17)	1.23 (21)	0.59	0.97 (19)	0.99 (26)	0.97
^{176}Lu	$7/2^+$	0.71 (17)	1.31 (16)	0.55	1.02 (17)	0.98 (11)	1.04
^{182}Ta	$7/2^+$	0.60 (7)	1.19 (15)	0.50	0.82 (6)	1.07 (11)	0.76
^{177}Lu	7^-	0.59 (10)	1.31 (13)	0.45			
All		0.73 (91)	1.19 (130)	0.62	0.96 (80)	1.02 (98)	0.94

In order to explore the statistical properties of the observed x distributions, a model was constructed for simulating the neutron capture and subsequent γ-decay. The capture states $\{i\}$ are assumed to be linear combinations of basis configurations $\{j\}$ weighted by Porter-Thomas distributed squared amplitudes $p_{i,j}$. Each configuration $\{j\}$ decays into one specific final state, for simplicity denoted with the same index j. The probability for each resonance to be populated is determined by the squared amplitude $p_{i,j(\text{entrance})}$ of the entrance component. The probability Γ_j for a transition to a given final state j from a total number n of populated resonances, is then given as the sum $\Gamma_j = \sum_{i=1}^{n} p_{i,j} \cdot p_{i,j(\text{entrance})}$. The theoretical x_j values are finally calculated as $x_j = \langle x\rangle_{\text{exp}} \cdot \Gamma_j/\langle\Gamma\rangle$, where $\langle x\rangle_{\text{exp}}$ is the experimental average for the ensemble considered, ensuring a distribution centroid $\langle x\rangle_{\text{theor}} = \langle x\rangle_{\text{exp}}$. Detailed information is given in Ref. [3].

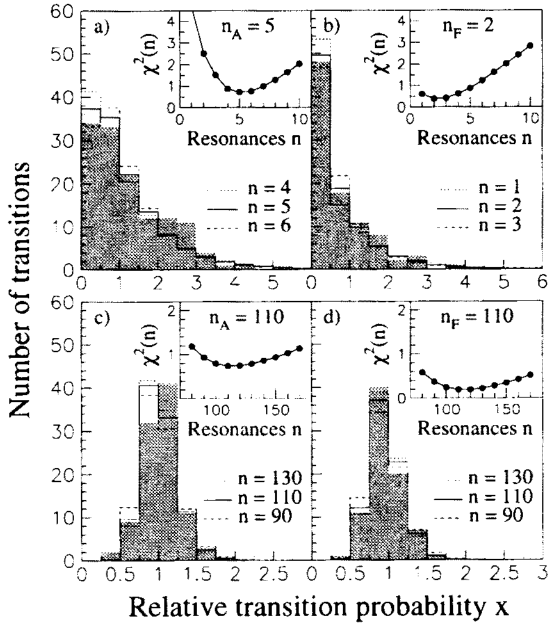

Fig. 1. Experimental distributions (filled histograms) of relative reduced transition probabilities x for *a*) allowed and *b*) forbidden transitions, thermal energies, and *c*) allowed and *d*) forbidden transitions, ARC energies. The data are compared with theoretical x distributions for different numbers n of resonances (open histograms). The inserts show the squared deviation χ^2 between calculated distributions and data for various n.

In the thermal case, comparison of data and model calculations shows that the K-allowed and K-forbidden x distributions, in addition to displaying different centroids, have shapes associated with different numbers n of degrees of freedom (populated resonances in the present model). As shown in Fig. 1 the allowed transitions form a distribution consistent with $n_A = 5$, while the distribution of forbidden transitions is well reproduced assuming $n_F = 2$. The observed ARC x distributions, both forbidden and allowed, are well described assuming the same number of initial states, $n_A = n_F \approx 110$. A satisfactory theory has to explain the astonishing difference between the x distributions for K-allowed and K-forbidden transitions, both with respect to centroids and shapes, in the thermal but not in the ARC data.

One possible explanation for the n_F–n_A difference could be K-mixing for only a subset of the neutron resonances. However, a model assuming two classes of resonance states with different degrees of K mixing is not consistent with the observation that $n_F \approx n_A$ in the ARC data.

Alternatively, the extra degrees of freedom might be connected with the decay instead of the population process. The question is then why the additional exit components, exclusive to the allowed decay, vanish in the ARC case. This might be possible if they are closely related to the entrance component, which to a large extent is prevented from contributing to the γ-decay at $E_n = 2$ keV due to rapid depletion by neutron emission. The mathematical implications of such an entrance-exit correlation remain to be explored in detail.

An intriguing question is whether there might be fundamental structural differences between the states populated by thermal and 2 keV neutrons. With an energy spread of several hundreds of keV, the ARC neutrons will populate an order of $\sim 10^2$ resonance states, dominating the cross section, and the resulting x distributions are expected to reflect resonance quantal properties. At thermal energies, the average resonance width is ~ 1 eV, and the spacing of the order of $\sim$10 eV for a given spin value. The thermal neutrons enter the nuclei at $E_n \approx B_n + 1/30$ eV with a very small energy spread, and are most likely to hit between two resonances, populating a narrow interval of their tail regions. One may speculate whether the cross section also includes some kind of nonresonant background states with less K mixing than the resonances. It is not clear how such states should be modelled mathematically. One possible contribution to the nonresonant cross section might be potential capture, where γ-decay takes place directly from the entrance component [4].

In summary, thermal neutron capture data reveal a striking difference between the probability distributions for primary transitions into "K-followed" and "K-forbidden" final states, both with respect to centroids $\langle x\rangle_F$ and $\langle x\rangle_A$, and shapes, associated with different numbers of degrees of freedom n_F and n_A. A weak K hindrance is also found at ARC energies, but no difference in the numbers of degrees of freedom n_F and n_A is apparent.

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