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THE CAPTURE OF THERMAL NEUTRONS BY EVEN-EVEN NUCLEI WITH A = 60-80

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ABSTRACT

The probability of a random anticorrelation between the reduced neutron and radiation widths in Zn^{69}, Ge^{71}, Ge^{73}, and Se^{81} nuclei is considered. It is shown that the anticorrelations observed in these nuclei following thermal neutron capture are nonrandom in nature.

The study of the γ-ray spectrum of the capture of thermal neutrons by even-even atomic nuclei with $A \leq 80$ showed that the hard part of the γ-ray spectrum has intensive γ lines, which cannot be explained within the framework of the statistical model of capture via the compound nucleus. For nuclei in the region $A \sim 50$ the intensive γ lines can be accounted for by direct capture of an s-neutron in the lower p-levels of the nucleus.[1] Direct capture of an s-neutron in nuclei with $A \sim 50$ is confirmed by the theoretically predicted correlation between the spectroscopic factors $(2J_f + 1)$s of the low-lying p-levels and the I_γ/E_γ^3 values, which are proportional to the reduced probabilities of the E1 transitions from the capture state of the nucleus to these levels.[2] However, recent observations have shown a lack of correlation in the individual levels (Ni^{63}, Zn^{65}, and Zn^{67}) (Refs. 2 and 3) and in a number of low-lying levels (Fe^{57}, Zn^{69}, Ge^{71}, Ge^{73}, and Se^{81}) (Refs. 2-8) of nuclei with $A \approx 60$-80. These anticorrelations are attributable to the presence in the capture state of an admixture of fairly simple configurations such as the doorway states.[2,8-13] However, the anticorrelations may also be of a random nature because of fluctuations in the distribution of the partial radiation widths of the capture state. In this paper we consider the probability of

random occurrence of anticorrelations between I_γ/E_γ^3 and $(2J_f + 1)$s in the capture of thermal neutrons by even-even nuclei with A ~ 70-80.

1. COMPARISON OF I_γ/E_γ^3 and $(2J_f + 1)$s FOR EVEN-ODD NUCLEI WITH A = 25-81.

The degree of correlation between I_γ/E_γ^3 and $(2J_f + 1)$s can be quantitatively determined by using the correlation coefficient

$$\rho = \sum_i (x_i - \bar{x})(y_i - \bar{y}) \left[\sum_i (x_i - \bar{x})^2 \sum_i (y_i - \bar{y})^2 \right]^{-1/2}, \qquad (1)$$

where x_i and y_i are the quantities I_γ/E_γ^3 and $(2J_f + 1)$s being compared and $\bar{x}$ and $\bar{y}$ are their average values. The quantity ρ can vary in the range of -1 to +1, which corresponds to the two extreme cases of total anticorrelation or total correlation. Because sufficiently reliable data on (n,γ) thermal neutron reaction and (d,p) reaction are now available for most nuclei with A = 25-81, the degree of correlation between I_γ/E_γ^3 and $(2J_f + 1)$s can be established fairly reliably by using the coefficient ρ. Figure 1 shows the dependence of the correlation coefficient ρ for even-odd nuclei with A = 25-81. The upper part of the figure shows the calculated values of ρ for the isotopes; the values compared are given in parentheses. Calculations were not performed for nuclei having only two El transitions (Si^{29}, Si^{31}, and Ca^{49}), since $\rho = \pm 1$ for the two values being compared. In calculating ρ the data on (n,γ) and (d,p) reactions were taken from the following sources: Mg^{25} (Refs. 14 and 15); S^{33} (Refs. 15 and 16); Ar^{37} (Refs. 15-17); Ar^{41} and $Ca^{41,43,45}$ (Refs. 18 and 19); Ti^{47} (Refs. 20 and 21); Ti^{49} (Refs. 17 and 22);

Cr^{51} (Refs. 23 and 24); Cr^{53} (Refs. 25 and 26); Fe^{55} (Refs. 17 and 27); Fe^{57} (Refs. 17, 28, and 29); Ni^{59} (Refs. 17, 30, and 31); Ni^{61} (Refs. 17, 28, and 30); Ni^{63} (Refs. 17 and 27); Ni^{65} (Refs. 27 and 32); $Zn^{65,67,69}$ (Refs. 3 and 33); $Ge^{71,73}$ (Refs. 5, 34, and 35); and $Se^{77,79,81}$ (Refs. 7, 8, and 36).

The data on the (d,p) reaction were taken primarily from experiments on deuterons of sufficiently high energy to eliminate the compound-nucleus effect in this reaction at low energy.[37] The large positive values of ρ for most of the nuclei with A = 25-67 confirm that the predicted s-direct neutron capture is the predominant mechanism in these nuclei.[1] Because of incomplete correlation the value of ρ is lower in some levels in Fe^{57} and Ni^{63} (Ref. 2); in Fe^{57}, for example, it is -0.014. Nonetheless, for Zn^{65} and Zn^{67} the values of ρ are positive and relatively large (+0.75 and +0.64, respectively), in spite of incomplete correlation.[2,3] Large negative values of ρ have also been observed in the Zn^{69} (-0.31), Ge^{71} (-0.41), Ge^{73} (-0.3), and Se^{81} (-0.43) isotopes. The negative values cannot be attributed to experimental error for several reasons: first, the value of ρ depends on the relative values of x_i and y_i; second, ρ is determined principally by the more intensive components of x_i and y_i; and third, the relative errors of the more intesnive I_γ/E_γ^3 and $(2J_f + 1)$s in the current experiments have not exceeded 5-10%.

Thus the experimental error of the negative ρ's is $\leq$15-20%.

2. CONNECTION BETWEEN THE COEFFICIENT ρ AND THE CAPTURE STATE OF THE NUCLEUS.

The correlation coefficient ρ can have different values, depending on the contribution of the configurations to the wave function of the capture state of the nucleus. If the contribution is governed by statistical laws, the distribution of the partial radiation widths and spectroscopic factors of the lower levels must be uncorrelated and the coefficient ρ will have values close to zero. An admixture of simple, single-particle s-states in the capture state produces a positive correlation between the El-transition probabilities in the lower p-levels and the spectroscopic factors $(2J_f + 1)s$ of these levels.[1] An anticorrelation between I_γ/E_γ^3 and $(2J_f + 1)s$ must be observed in the γ decay of certain simple configurations such as the doorway states.[2,8]

It should be noted that the values of ρ close to zero can occur as a result of de-excitation of a large number of compound states of the compound nucleus and also when the contribution from the direct capture is equal to that from the decay of the doorway states, which leads to anticorrelation. The latter can occur in an Fe^{57} nucleus in which an anticorrelation, which is compensated by intensive correlation transitions to the first excited levels, has been established for most levels.

Isolated instances of noncorrelation in Ni^{63}, Zn^{65}, and Zn^{67} nuclei are attributable to the doorway states[2] and to structural fluctuations of the nearest resonance of the compound nucleus. These factors can also account for the negative values of ρ obtained for Zn^{69}, $Ge^{71,73}$, and Se^{81}.

The absolute values of the negative coefficients ρ for Zn^{69}, $Ge^{71,73}$, and Se^{81} are not as high as those of the positive coefficients for A = 25-67. This is attributable to the admixture of the direct capture in the $2p_{1/2}$ state. Moreover, not all types of excited doorway states lead to anti-correlations between I_γ/E_γ^3 and $(2J_f + 1)$s. In the case of Zn^{69}, Ge^{71}, and Se^{81} nuclei, whose odd neutron in the ground state is in the $2p_{1/2}$ state, the following three-quasiparticle doorway states, which indicate a correlation between I_γ/E_γ^3 and $(2J_f + 1)$s following γ-ray decay, can be excited:

$$[(p^4_{3/2})_n(s_{1/2})_n]^3_{1/2^+} \to [(p^{-1}_{3/2})_n(p_{1/2})_n(d^3_{3/2})_n]^4_{1/2^+} \xrightarrow{E1} [(p^3_{3/2})_n(p_{1/2})_n]^1_{1/2^-}, \tag{2}$$

$$[(p^4_{3/2})_n(s_{1/2})_n]^3_{1/2^+} \to [(p^{-1}_{3/2})_n(p_{1/2})_n(d^3_{3/2})_n]^4_{1/2^+} \xrightarrow{E1} [(p^{-1}_{3/2})_n(p^2_{1/2})_n]^1_{3/2^-}. \tag{3}$$

3. STATISTICAL PROBABILITY OF DEVIATION-FROM-ZERO VALUES OF THE COEFFICIENT ρ.

According to the statistical model, the distribution of $\Gamma_{\gamma i} \propto I_\gamma/E_\gamma^3$ is independent of the $(2J_f + 1)$s distribution, and if the values x_i and y_i being compared are finite in number, the coefficient ρ will have random values between -1 and +1, following a definite probability. The probability distribution of the coefficient ρ for different numbers of the x_i and y_i values being compared was calculated by the Monte Carlo method. The probability distributions I_γ/E_γ^3 and $(2J_f + 1)$s were assumed to correspond to the χ^2 distribution law with one degree of freedom:

$$P(x)\,dx = e^{-x/2}dx / \sqrt{2\pi x}. \qquad (4)$$

Although this approximation seems to be justified for the γ decay of the compound capture state,[38,39] it can hardly be justified for the lower excited levels of a simpler nature. However, if the lower levels are sufficiently large in number as, for example, in Ge^{73}, the distribution of the spectroscopic factors, which has been calculated for the 22 lower levels being considered, indicates that the agreement with the χ^2 distribution law with one degree of freedom (Fig. 2) is fairly good.

The results of the calculations for Se^{81}, Zn^{69}, Ge^{71}, and Ge^{73} nuclei (the number of values being compared is n = 6, 10, 12, and 22, respectively) are shown in Fig. 3. All the distributions cited were normalized to a single value. The probability distributions obtained have an asymmetric form because of the unequal distribution of the probability (4) of the x_i and y_i values being compared. The probabilities for the random occurrence of negative values of ρ are: Se^{81}, 34% ($\rho \leq -0.43$, n = 6); Zn^{69}, 17.2% ($\rho \leq -0.31$, n = 10); Ge^{71}, 4.4% ($\rho \leq -0.41$, n = 12); and Ge^{73}, 4.7% ($\rho \leq -0.3$, n = 22). Thus the probability for the random occurrence of negative values of ρ is fairly low, especially for the Ge^{71} and Ge^{73} isotopes. If we consider that the values used to obtain the negative values of ρ given above included some that had a positive correlation because of direct capture and excitation of types (2) and (3) doorway states, we may conclude that the negative values of ρ are not

random. The negative coefficient ρ for Ge^{73} is -0.41 for the first 11 values being compared, which corresponds to the γ-ray transitions to the levels with energy lower than 1.3 MeV. As can be seen from Fig. 3, since the probability of random occurrence of $\rho \leq -0.4$ for $n = 11$ is approximately the same as that of $\rho \leq -0.3$ for $n = 22$, the eleven values being compared, which correspond to the γ-ray transitions to the levels with energy above 1.3 MeV in Ge^{73}, must be distributed independently of one another; i.e., the given γ-ray transitions correspond to the decay of the compound states of the compound nucleus. This is borne out by the small intensities of the γ-ray transitions. Thus the result obtained for Ge^{73} shows that the doorway states produced in this nucleus decay principally to the lower levels with energy below 1.3 MeV.

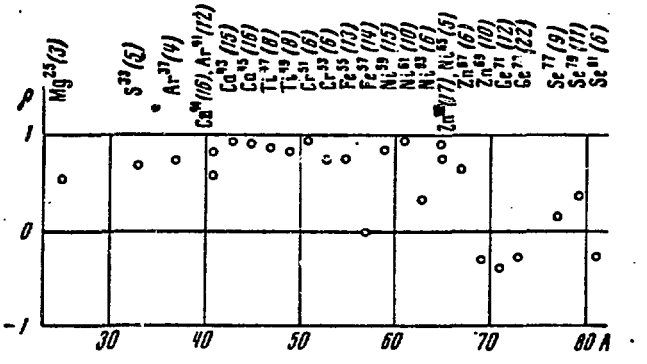

Figure 1. Correlation coefficient ρ for I_γ/E_γ^3 and $(2J_f + 1)$s for even-odd nuclei with A = 25-81.

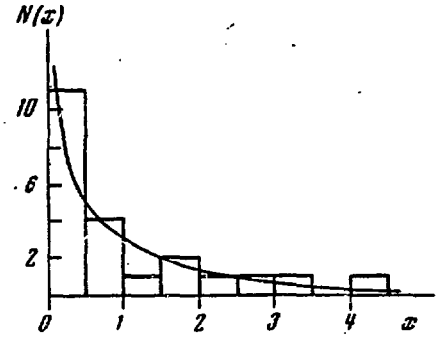

Figure 2. Distribution of spectroscopic factors $(2J_f + 1)s$ for 22 lower levels of Ge^{73}; $x = (2J_f + 1)s/[(2J_f + 1)s]_{av}$ is plotted along the X-axis.

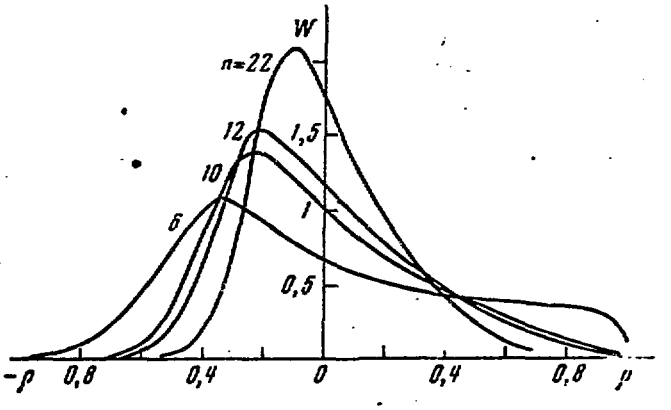

Figure 3. Probability distribution of the correlation coefficient ρ for the n values compared (the numbers pertain to the curves);

$$\rho = \sum_i (x_i - \bar{x})(y_i - \bar{y}) \Big/ \left[\sum_i (x_i - \bar{x})^2 (y_i - \bar{y})^2\right]^{1/2}; \quad P(x)\,dx = e^{-x/2}\,dx/\sqrt{2\pi x}\,.$$

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