SYSTEMATICS OF *K*-FORBIDDEN GAMMA-RAY TRANSITION PROBABILITIES

A. P. Lashko**, *T. N. Lashko

Institute for Nuclear Research, 03680, Kyiv, Ukraine

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All available experimentally determined absolute γ-ray transition probabilities in odd- and even-mass nuclei of the rare earth region (with neutron numbers $89 \leq N \leq 116$ and proton numbers $60 \leq Z \leq 78$) and of the actinide region ($N \geq 138$) have been analyzed. 432 K-forbidden γ-ray transitions have been identified. The Weisskopf hindrance factor F_W for $E1$, $E2$, $E3$, $M1$, and $M2$ transitions has been calculated; empirical relations between $\log F_W$ values and the degree of K-forbiddenness have been determined.

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1. INTRODUCTION

In deformed nuclei γ-ray transition probabilities between states with different values of the quantum number K (K being the projection of the angular momentum onto the nuclear symmetry axis) are substantially dependent on the magnitude of this difference. If the difference in K-quantum number $|\Delta K|$ is larger than the multipole order L, electromagnetic transitions are called forbidden. The degree of K-forbiddenness ν is defined as

$$\nu = |\Delta K| - L. \qquad (1)$$

In order to characterize the probabilities of such transitions the Weisskopf hindrance factor F_W is used. It is defined as the ratio of experimental γ-ray transition probabilities to the Weisskopf estimate:

$$F_W = \frac{T_{(1/2)\gamma}(experimental)}{T_{(1/2)\gamma}(Weisskopf estimate)}, \qquad (2)$$

where $T_{(1/2)\gamma}$ is the partial γ-ray half-life.

There is a correlation between the Weisskopf hindrance factor F_W and the degree of K-forbiddenness ν . According to the "empirical rule" proposed by Rusinov [1]:

$$\log F_W = 2 \times (|\Delta K| - L). \qquad (3)$$

This estimate of the K-forbidden γ-ray transition probabilities is very rough and holds true approximately, which was clearly shown by Löbner [2]. Unfortunately, the author did not offer an alternative relation. At the same time, such estimates are very useful and essential for nuclear spectroscopy. We have made significant progress on this issue [3].

2. THE RESULTS AND DISCUSSIONS

All available experimentally determined absolute γ-ray transition probabilities in odd- and even-mass nuclei of the rare earth region (with neutron numbers $89 \leq N \leq 116$ and proton numbers $60 \leq Z \leq 78$) and of the actinide region ($N \geq 138$) from the Evaluated Nuclear Structure Data File (ENSDF - September 2014 version) [4] have been analyzed. 432 K-forbidden γ-ray transitions have been identified. The number of cases of transitions with given multipolarity and the degree of K-forbiddenness are distributed according to transition type as follows (Figs.1 and 2).

The Weisskopf hindrance factor F_W and empirical relations of $\log F_W$ values on the degree of K-forbiddenness have been calculated for all of these transitions. As a result, more realistic estimates of such γ-ray transition probabilities have been obtained (Figs.3-7).

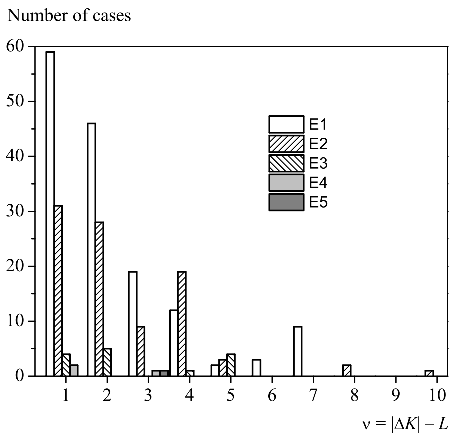

Fig.1. *The experimental data on the probabilities of K-forbidden electric γ-ray transitions*

*Corresponding author E-mail address: anatolii.lashko@gmail.com

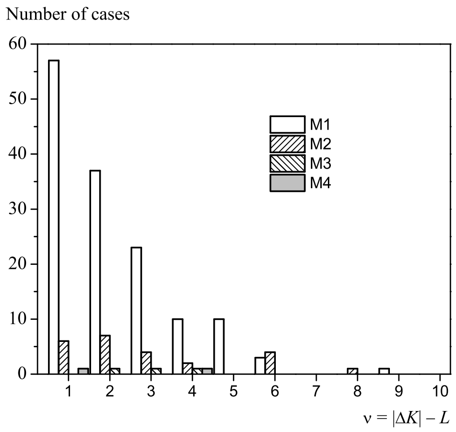

Fig.2. *The experimental data on the probabilities of K-forbidden magnetic γ-ray transitions*

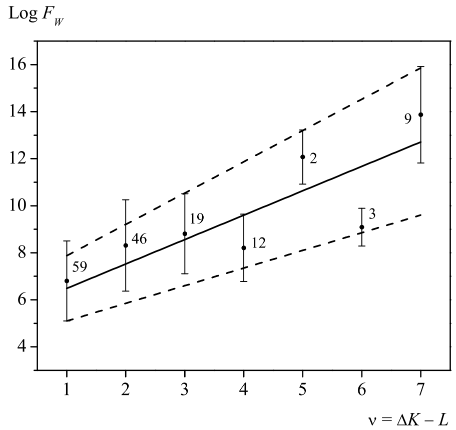

Fig.3. *Relation between the Weisskopf hindrance factor* F_W *and the degree of K-forbiddenness* $\nu = |\Delta K| - L$ *for the E1 transitions. The parameters for interpolation formula are the following:* $a = 5.5 \pm 1.1$, $b = 1.0 \pm 0.3$ *(see text for explanation)*

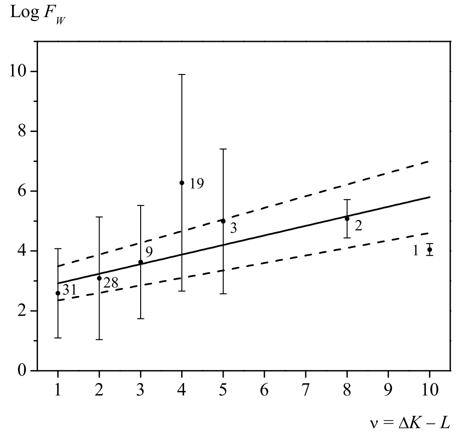

Fig.4. *Relation between the Weisskopf hindrance factor* F_W *and the degree of K-forbiddenness* $\nu = |\Delta K| - L$ *for the E2 transitions. The parameters for interpolation formula are the following:* $a = 2.6 \pm 0.5$, $b = 0.3 \pm 0.1$

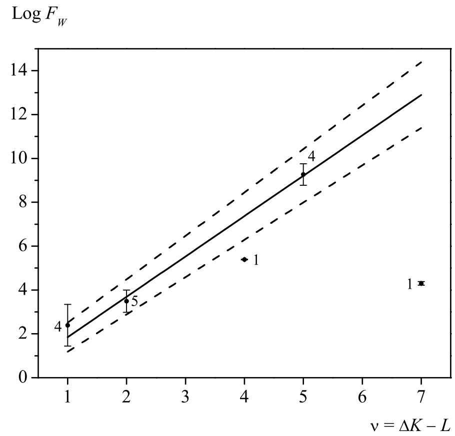

Fig.5. *Relation between the Weisskopf hindrance factor* F_W *and the degree of K-forbiddenness* $\nu = |\Delta K| - L$ *for the E3 transitions. The parameters for interpolation formula are the following:* $a = 0.0 \pm 0.5$, $b = 1.8 \pm 0.2$

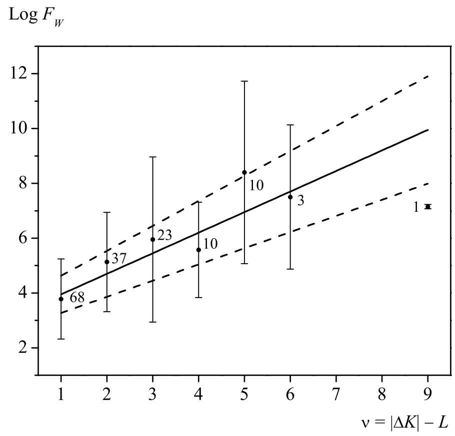

Fig.6. *Relation between the Weisskopf hindrance factor* F_W *and the degree of K-forbiddenness* $\nu = |\Delta K| - L$ *for the M1 transitions. The parameters for interpolation formula are the following:* $a = 3.2 \pm 0.5$, $b = 0.8 \pm 0.2$

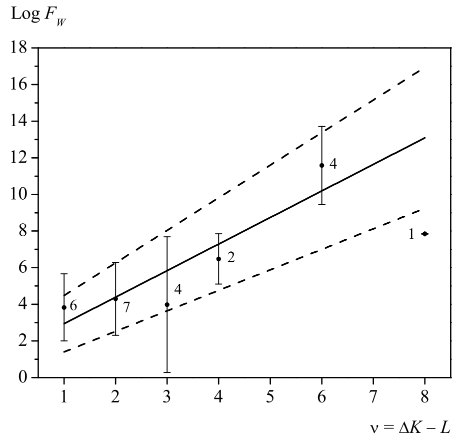

Fig.7. *Relation between the Weisskopf hindrance factor* F_W *and the degree of K-forbiddenness* $\nu = |\Delta K| - L$ *for the M2 transitions. The parameters for interpolation formula are the following:* $a = 1.5 \pm 1.2$, $b = 1.5 \pm 0.3$

The dependencies of the Weisskopf hindrance factor values F_W on the degree of K-forbiddenness $\nu = |\Delta K| - L$ are given for $E1$, $E2$, $E3$, $M1$, and $M2$ transitions. The numbers near the error bars indicate the number of γ-ray transitions with known transition probabilities corresponding to F_W values in this range for this type of transition. The solid lines are defined by the following equation: $\log F_W = a + b \times (|\Delta K| - L)$. The parameters for interpolation formulas were found by the least-square method. Dashed lines indicate a 68% confidence interval.

Our estimates of the K-forbidden γ-ray transition probabilities are similar to the "empirical rule" of Rusinov for $M2$ and $E3$ transitions and are significantly different for the $M1$, $E1$ and $E2$ transitions. The lack of experimental data did not allow us to determine such relations for $M3$, $M4$, $E4$, and $E5$ transitions.

Empirical dependencies for $E1$, $E2$, $E3$, and $M1$ transitions with similar values of the interpolation lines parameters were also obtained by the authors of Ref. [5].

The reduced hindrance factor f_ν (hindrance per degree of K-forbiddenness) is often used in nuclear spectroscopy for systematics of K-forbidden transition probabilities:

$$f_\nu = (F_W)^{1/\nu}. \qquad (4)$$

The dependence of the $\log f_\nu$ values on the degree of K-forbiddenness $\nu = |\Delta K| - L$ for $E1$ transitions is shown in Fig.8. The figure clearly shows that the correlation mentioned above is well described by a polynomial of the second degree, while a linear relation can be observed for the $logF_W$ values. The same holds true for other transitions as well. However, we believe that using empirical relations shown in Figs.3-7 for evaluation of the K-forbidden γ-ray transition probabilities is preferred.

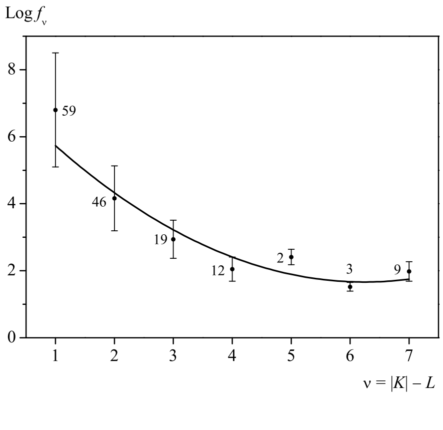

Fig.8. *Relation of the reduced hindrance factor $f_\nu = (F_W)^{1/\nu}$ on the degree of K-forbiddenness $\nu = |\Delta K| - L$ for the E1 transitions. The solid line is defined by the equation $\log f_\nu = a + b\nu + c\nu^2$. The parameters are: $a = 7.4 \pm 2.2$, $b = -(1.9 \pm 0.9)$, $c = 0.15 \pm 0.09$*

The empirical formulas for the calculation of the K-forbidden γ-ray transition probabilities, which have been derived in this paper, should be used in experiments on the search for high-multipolarity transitions excited by discharging of K-isomers to the levels of rotational bands of the parent nucleus. The methodology of such calculations has been described in detail in Ref. [6].

3. CONCLUSIONS

In conclusion, we would like to note the following. This systematics of K-forbidden gamma-ray transition probabilities can be used for verification of experimental data on the probability of such transitions, especially when it comes to the data obtained in a single work.

Let us consider Fig.5 as an example. The figure describes the experimental value of the Weisskopf hindrance factor F_W for the $E3$ transition with $\nu = 7$ to be significantly different from interpolation line. It is the transition with the energy of 39 keV discharging 1705 keV isomeric state $IK^\pi = 10\ 10^-$ ($T_{1/2}$=9.9 min) to the 1666 keV level, $IK^\pi = 8\ 0^+$ of the ground state rotational band of ^{190}Os. $M2$+$E3$ multipolarity with the multipole mixing ratio $\delta(E3/M2) = 0.0094 \pm 0.0008$ has been calculated by an evaluator [7] based on conversion data of Ref. [8, 9]. The authors of papers mentioned claim that this transition has $M2$ multipolarity. Experimental value of the Weisskopf hindrance factor F_W for the $M2$ transition with $\nu = 8$ is in good agreement with empirical dependence of F_W on the degree of K-forbiddenness for $M2$ transition (see Fig.7). From our point of view, such large value of the admixture of $E3$ multipolarity is caused by mistakes in the calculation of experimental errors by the authors [8, 9].

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СИСТЕМАТИКА ВЕРОЯТНОСТЕЙ *K*-ЗАПРЕЩЁННЫХ ГАММА-ПЕРЕХОДОВ

А. П. Лашко, Т. Н. Лашко

Были проанализированы все доступные экспериментальные данные о вероятностях γ-переходов в нечётных и чётных ядрах области редких земель (с числом нейтронов $89 \leq N \leq 116$ и числом протонов $60 \leq Z \leq 78$) и области актинидов ($N \geq 138$). Идентифицированы 432 K-запрещённых γ-перехода. Для переходов $E1$-, $E2$-, $E3$-, $M1$- и $M2$-мультипольностей рассчитаны факторы задержки Вайскопфа F_W и определены эмпирические зависимости величины $\log F_W$ от степени запрета.

СИСТЕМАТИКА ЙМОВІРНОСТЕЙ *K*-ЗАБОРОНЕНИХ ГАММА-ПЕРЕХОДІВ

А. П. Лашко, Т. М. Лашко

Були проаналізовані всі доступні експериментальні дані про ймовірності γ-переходів в непарних і парних ядрах рідкоземельної області (з числом нейтронів $89 \leq N \leq 116$ і числом протонів $60 \leq Z \leq 78$) і області актиноїдів ($N \geq 138$). Ідентифіковані 432 K-заборонені γ-переходи. Для переходів $E1$-, $E2$-, $E3$-, $M1$- і $M2$-мультипольностей розраховані фактори затримки Вайскопфа F_W та визначені емпіричні залежності величини $\log F_W$ від ступеня заборони.