FORBIDDEN E1 TRANSITIONS IN Tb^{159} *AND* Yb^{173}

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Submitted to JETP editor May 5, 1961

J. Exptl. Theoret. Phys. (U.S.S.R.) **41**, 1704-1709

Two half-lifes are measured: $T_{1/2} = (1.7 \pm 0.7) \times 10^{-10}$ sec for the 364-kev level of Tb^{159} and $T_{1/2} = (4.2 \pm 0.7) \times 10^{-10}$ sec for the 351-kev level of Yb^{173}. The E1 transition probabilities are calculated and compared with the values derived from the Nilsson model. It is concluded that, just as in the case of Hf^{177}, E1 transitions occur in both nuclei with probabilities differing widely from the theoretical values.

THE probability ratio of the 208- and 321-kev E1 transitions in Hf^{177} disagrees strongly with the Alaga formula.[1] However, it has been shown that the probability of the 208-kev transition is close to the value calculated from the Nilsson model, whereas disagreement by a factor of about 400 results for the 321-kev transition.[2] It is interesting to consider whether this occurs for all E1 transitions of deformed nuclei, to which the Alaga formula cannot be applied.

Table I shows disagreement with the Alaga formula for E1 transitions forbidden by the asymptotic selection rules in Tb^{155}, Tb^{157}, Tb^{159}, Yb^{173}, and Lu^{175}.[3] In the present work we measured the absolute probabilities of E1 transitions in Tb^{159} and Yb^{173}.

THE Tb^{159} NUCLEUS

The decay of Gd^{159} has been studied in[4], where the character and intensity ratio of γ transitions were calculated. An upper limit $T_{1/2} \leq 5 \times 10^{-10}$ sec was obtained for the half-life of the 364-kev level. Metzger and Todd,[5] using the resonance scattering method, obtained $\tau = (2 \pm 0.3) \times 10^{-10}$ sec for the mean life of this level, whereas in the present work we have used delayed β-γ coincidences. The 364-kev photons were detected with a NaI(Tl) crystal, while β radiation was detected with an anthracene crystal. We used FÉU-33 photomultipliers and a "fast-slow" coincidence circuit with 6×10^{-9} sec resolving time.[6]

The time distribution of delayed coincidences was compared with an instantaneous resolution curve for a Ru^{103} source used under the same conditions (Fig. 1). The centers of gravity of the two curves are separated by $\tau = (2.5 \pm 1) \times 10^{-10}$ sec; this indicates $T_{1/2} = (1.7 \pm 0.7) \times 10^{-10}$ sec for the half-life of the 364-kev level.

Three γ quanta with energies 225, 307, and 364 kev are emitted from the 364-kev level. The conversion coefficient of 364-kev radiation[4,5] indicates an E1 transition. Malik et al[7] assign an E2 + M1 character to this transition. Nathan and Popov[8] used Coulomb excitation of Tb^{159} to investigate the 364-kev level, and calculated the reduced electric transition probability B(E2). The latter authors showed that E1 and E2 transitions cannot be distinguished. Taking their value for B(E2), $T_{1/2} \approx 10^{-9}$ sec is obtained for the 364-kev level.

However, the results obtained by Coulomb excitation and delayed coincidences agree in general.[9] We can therefore conclude that the given transition is more likely to be of E1 character.

Toth and Nielsen[10] have recently studied the 327- and 227-kev levels of Tb^{157} and Tb^{155}, respectively, from which E1 quanta are emitted. The intensity ratios for these nuclei are given in

Table I. Ratios of reduced E1 transition probabilities

Nucleus	Transition energy, kev	Experimental ratio	Theoretical ratio (strong interactions)
Tb^{155}	227; 161	1 : 0.007	1 : 0.43
Tb^{157}	327; 265; 183	1 : 0.0075 : 0.105	1 : 0.43 : 0.07
Tb^{159}	364; 307; 225	1 : 0.013 : 0.12	1 : 0.43 : 0.07
Yb^{173}	351; 272; 171	1 : 57 : 39	1 : 0.3 : 0.037
Lu^{175}	396; 282; 145	1 : 1.4 : 1	1 : 0.125 : 0.0125
Hf^{177}	321; 208	1 : 100	1 : 0.125

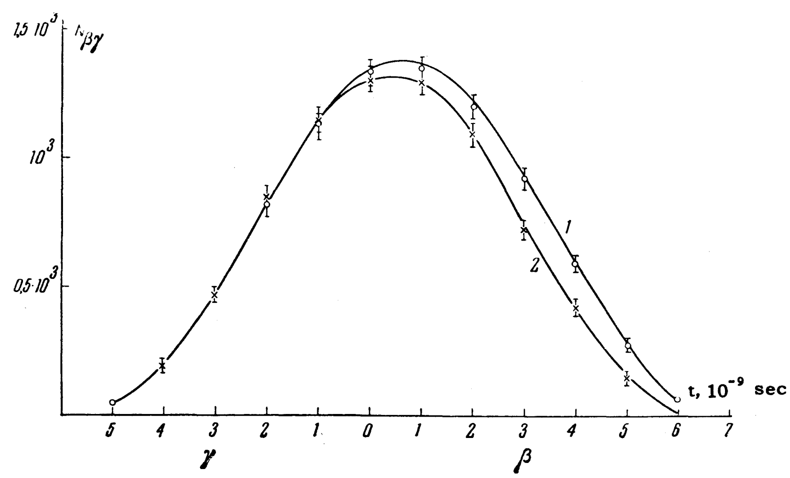

FIG. 1. Delayed-coincidence curves. 1 – Gd^{159}, $\beta-\gamma_{364}$; 2 – Ru^{103}, $\beta-\gamma_{364}$ (selecting pulses produced by Compton electrons recoiling from 495-kev γ rays). Pulse delays are represented to the left of zero on the horizontal axis for the γ counter, and to the right for the β counter.

Table II

Nucleus	Transition energy, kev	Ratio of calculated (from Weisskopf formula) to experimental M2 transition probability*	Nucleus	Transition energy, kev	Ratio of calculated (from Weisskopf formula) to experimental M2 transition probability*
Tb^{159}	225	0.8	Lu^{175}	396	1.3
Tm^{169}	63	0.35—3.5		282	2
Yb^{173}	351	0.8	Hf^{177}	208	1.1
	171	0.55	Lu^{177}	147	0.8

*For transitions where the E1/M2 ratio in the E1 + M2 mixture is known.

Table I. The Tb^{159} nucleus is very similar to Tb^{157} and Tb^{155} [10]; this furnishes an additional argument in favor of assigning E1 character to the 364-kev transition.[4,5] Using the results given in [4] for the intensity ratio and conversion coefficients of 364-kev E1 radiation and 225-kev E1 + M2 radiation in Tb^{159}, we computed the following transition probabilities:

$$P_{364}(E\,1) = 4\cdot10^{9}\text{sec}^{-1}, \qquad P_{225}(E\,1) = 1.2\cdot10^{8}\text{sec}^{-1}.$$

As in the case of the M2 radiation in mixed E1 + M2 transitions observed in rare earth elements, we find that the transition probability of a 225-kev M2 transition is in good agreement with the value calculated from the Weisskopf formula (Table II).

The conversion coefficient for the 307-kev transition has not been measured. We obtain the percentage of M2 in the 307-kev transition by assuming that the Alaga formula holds for unforbidden M2 transitions [1,6]. The result E1/M2 = 2.7 gives $P_{307}(E1) = 3 \times 10^{7}$ sec^{-1}.

By comparing these E1 transition probabilities with values computed from the Nilsson formula,[2] we obtain the different degrees of forbiddenness:

$$f_{N364} = 10, \qquad f_{N225} = 6, \qquad f_{N307} = 300.$$

THE Yb^{173} NUCLEUS

Lu^{173} decay has been studied by two groups of investigators,[11,12] who obtained the γ-ray ratios and conversion coefficients. By using these values and assuming that the Alaga and Weisskopf formulas are applicable to unforbidden M2 transitions (Table II) we arrive at an order of magnitude for the half-life of the 351-kev level. It must be noted that the conversion coefficients for the 171-, 272-, and 351-kev transitions and the intensity of the 351-kev transition obtained by Bichard et al[12] differ from the results given in [11]. Taking the results given in [12], we find that the ratio $B_{272}(M2)/B_{351}(M2)$ is 225 times larger than the theoretical result, whereas M2 transitions are allowed. These results therefore appear to be incorrect. From the M2 percentage in 351- and 171-kev radiation and the intensity ratios in [11] we obtain $T_{1/2} \approx 7 \times 10^{-10}$ sec for the half-life of the 351-kev level.

MEASUREMENT OF THE HALF-LIFE OF THE 351-kev LEVEL

The Lu^{173} nucleus is converted by electron capture to Yb^{173} in a 351-kev excited state, from which it goes to the ground state mainly by the cascade emission of 272- and 79-kev γ rays. The half-life of the 351-kev level can be measured by using x_{capt}-γ_{272} delayed coincidences. For the purpose of detecting 50-kev x rays and 272-kev γ rays we used two NaI(Tl) crystals; the resolving time of the system was 9×10^{-9} sec. The channel registering capture x rays also registered x rays from a 79-kev conversion transition. We

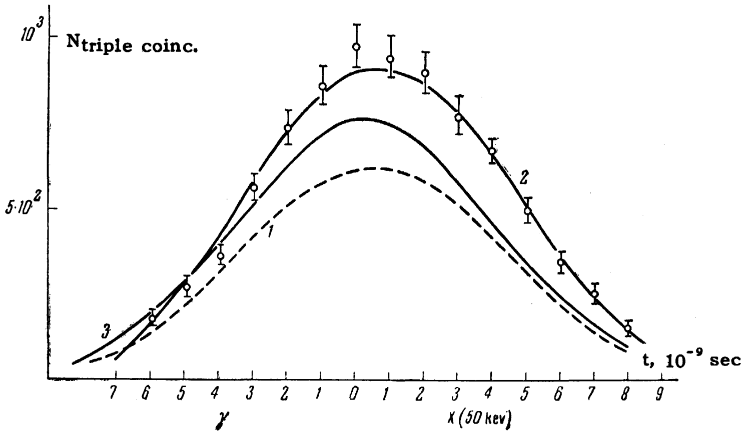

FIG. 2. Delayed-coincidence curves. 1 – Lu^{173}, $x_{conv} + x_{capt} - \gamma_{272}$; 2 – Lu^{173}, $x_{capt} - \gamma_{272}$ (computed curve and experimental points); 3 – Na^{22}, $\gamma_{511} - \gamma_{272}$ (with registration in both instances of pulses equivalent to those produced by Compton electrons recoiling from 510-kev γ rays).

thus obtained a combined $x_{capt} + \gamma_{conv} - \gamma_{272}$ coincidence curve (curve 1 in Fig. 2).

The pure x_{capt}-γ_{272} curve can be derived either by subtracting the x_{conv}-γ_{272} curve from curve 1, or by measuring x_{capt}-γ_{79} triple coincidences.

The x_{conv}-γ_{272} curve can be computed from knowledge of the conversion coefficient for the 79-kev transition, the 79-kev level lifetime,[13] and the K/L capture ratio for the transition to the 351-kev level.[11] Curve 2 is calculated by subtracting the x_{conv}-γ_{272} curve from curve 1. Figure 2 shows the experimental results for triple coincidences, which fit well the computed curve 2. Curve 3 is the instantaneous resolution curve for Na^{22}. The separation of the centers of gravity of curves 2 and 3 gives the mean lifetime $\tau = (6 \pm 1) \times 10^{-10}$ sec and half-life $T_{1/2} = (4.2 \pm 0.7) \times 10^{-10}$ sec. The latter agrees well with the result $(4.7 \pm 0.3) \times 10^{-10}$ sec given in[14].

The measured half-life of the 351-kev level is of the same order as that computed from data in[11], while assuming that the Alaga and Weisskopf formulas are valid for allowed M2 transitions.

The following probabilities were calculated for 351-, 272-, and 171-kev E1 transitions:

$$P_{351}(E1) = 4.7 \cdot 10^7\ \text{sec}^{-1}, \quad P_{272}(E1) = 1.35 \cdot 10^9\ \text{sec}^{-1},$$

$$P_{171}(E1) = 1.65 \cdot 10^8\ \text{sec}^{-1}.$$

By comparing these results with the analogous values calculated by means of the Nilsson functions,[2] we obtain the corresponding degrees of forbiddenness f_N:

$$f_{N351} = 530, \quad f_{N272} = 2.5, \quad f_{N171} = 0.7.$$

Table II gives the ratio between the M2 transition probabilities for Yb^{173} calculated from Weisskopf's formula and the experimental values (when the M2/E1 ratio is known from[11]).

DISCUSSION OF RESULTS

Table III gives information regarding the E1 transition probabilities obtained by us together with other known analogous probabilities of transitions in rare earth elements.[15,16] For one group of these E1 transitions the experimental probabilities agree with the theoretical values derived

Table III

Nucleus	Transition energy, kev	Ratio of computed (from Nilsson formula) to experimental E1 transition probability		Nucleus	Transition energy, kev	Ratio of computed (from Nilsson formula) to experimental E1 transition probability	
		First group	Second group			First group	Second group
Eu^{153}	98	⩽5		Dy^{161}	25.8	1.2	
Gd^{155}	86	2.3			75		40
	106	2.5		Tm^{169}	63	0.6	
Tb^{155}	227	?			272	2.5	
	161		?	Yb^{173}	171	0.7	
	327	?			351		530
Tb^{157}	183	?			282	10	
	265		?	Lu^{175}	145	1.35	
	364	10			396		100
Tb^{159}	225	6		Hf^{177}	208	0.6	
	307		300		321		400
				Lu^{177}	147		250

from the Nilsson model,[2] the ratios being less than 10. The remaining transitions comprise a second group in which the ratios vary from 40 to 530.

In the cases of Dy^{161} and Lu^{177} the given discrepancy would normally be expected, since the Nilsson model is only an approximation and cannot account for all E1 transitions in deformed nuclei. However, it appears strange that E1 radiation belonging to both groups in Table III can sometimes come from the same nucleus. These represent transitions from the same excited level to two different rotational levels belonging to a single band. The strong coupling approximation holds for these nuclei, so that the Alaga formula is applicable.

It would be interesting to consider whether the rotation-single-particle or rotation-vibration interactions observed in Tb^{159}, Lu^{175}, and Hf^{177} (which have little effect on energy levels or on the probabilities of unforbidden γ transitions) can appreciably change the probabilities of forbidden E1 transitions.

In conclusion we wish to thank A. I. Alikhanyan for his interest.

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Translated by I. Emin
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