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ANALYSIS OF ^{165}Er EXCITED STATE PROPERTIES

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A precise energy and intensity of the γ-rays and the conversion electrons measurements together with the determination of the angular correlation coefficients for a cascade γ-ray transitions give a new opportunity for the determination of a multipole mixture and a branching of unresolved γ-rays. As an example we can use the ^{165}Tm decay.

A great number of papers deal with the excited state properties of strongly deformed nucleus ^{165}Er. We shall mention only those, the results of which are important for the analysis of quantum characteristics of 242.9, 589.8, 589.9, 746.9, 930.7, 1103.5 keV states and multipolarity of gamma-transitions between these states [1-13].

Recent [13] thorough measurements of internal conversion coefficients for the most of gamma-transitions occurring during ^{165}Tm decay and angular correlations of the 347-243 keV cascade, which we studied earlier [8], allow more definite conclusions on quantum characteristics of a double* upper state at 590 keV, as well as to substantiate other doublet transitions with the energy 156.2, 330.8, 513.7 keV, energy difference being 150 eV and less (Fig.1), and to determine multipolarities and intensities of these doublet transitions components.

In Fig.1 the brackets include values suggested by us. Energies of doublet transitions are calculated through difference of the known level energies [13].

The doublet structure of the state at 590 keV has been proved in papers [1,4,5,6,10,13], and it follows from the results of nuclear reaction studies [3,9,12] that the lower state of a doublet is a rotational level with the characteristics $3/2^+$ 1/2 [660]. At the same time Marguier [6] showed that the interaction between the subshells with N=2 allowed to consider the structure of the state as mixture of $1/2^+$ [660] and $1/2^+$ [400].

At the initial stage of the investigation $1/2^-$ or $3/2^-$ spins were assigned to the upper state of the doublet because of ambiguity in determining multipolarities of transitions binding this level.

* In this paper we used the term "doublet" for levels or gamma-transitions which differ in energy by 150 eV or less.

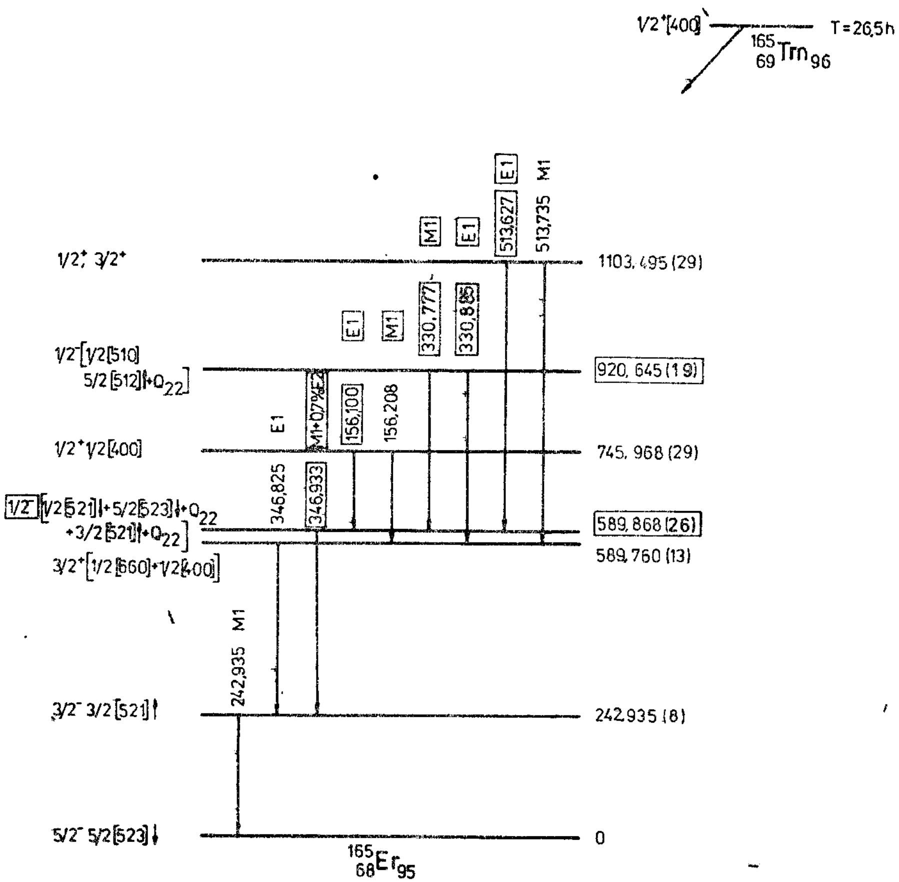

Fig. 1. A part of ^{165}Tm decay scheme.

Soloviev's calculations [2] made more definite the nature of the negative parity level at 590 keV assuming it to be a collective state with K=1/2⁻ (1/2⁻ 1/2 [521] ; 5/2 [523] + + Q_{22}; 3/2 [521] + Q_{22}). This assumption can be confirmed only through accurate determination of 330.8 keV transition multipolarity taking account of the fact that 920.74 keV level, according to papers [2,3,6], is a collective state with the characteristics 1/2⁻ (1/2 [510] + {5/2 [521] + Q_{22}}).

Table 1 shows the data on determining the multipolarity of the 330.8 keV transition. Noteworthy is the most accurate determination of α_k [13] of this transition. The authors make a conclusion that this is E2 transition. Although the α_k value

Table 1

Internal conversion coefficients of the transitions with the energy 156.2, 330.8, 346.9, 513.7 keV.

E_γ (keV)	Paper-Year		α_k exp.	Multipolarity	α_k theor. /14/ E1	E2	M1
156.199	/6/	1971	1.2 (-1)	E1	8.5 (-2)	3.5 (-1)	6.5 (-1)
	/11/	1980	3.1±1.0 (-1)	E2			
	/4/	1967	1.3 (-1)	M1			
	/5/	1970	6.5 (-2)	M1, E2			
330.824	/6/	1971	9 (-2)	M1	1.2 (-2)	3.8 (-2)	8.8 (-2)
	/11/	1980	7.58 (-2)	M1 + E2			
	/13/	1981	4.52±0.23 (-2)	E2			
	/4/	1967	6.1 (-2)	M1 + E2			
	/5/	1970	5.5 (-2)	M1			
346.926	/11/	1980	1.25 (-1)	M1	1.1 (-2)	3.3 (-2)	7.9 (-2)
	/13/	1981	7.4±0.4 (-2)	M1			
	/4/	1967	2.5 (-2)	M1 (+E2)			
	/5/	1970	0.9 (-2)	M1 , E2			
513.718	/6/	1971	2.7 (-2)	M1	4.5 (-3)	1.3 (-2)	2.8 (-2)
	/13/	1981	2.22±0.27 (-2)				

Table 2

Results of measurements of gamma-gamma angular correlations in ^{165}Er

Level energy (keV)	Cascade (keV)	A_{22}	A_{44}
589.9			
242.9	346.9–242.9	+0.057±0.011	−0.034±0.038
0.0			

somewhat exceeds the table value for the E2 transition, i.e., M1 admixture is possible, this conclusion leads us to determination of the doublet upper state spin as $J^{\pi}=3/2^-$.

One can check how it agrees with the data of the correlation experiment [8]. During the experiment measurements were done on the gamma-gamma angular correlation set up using a Ge(Li) - detector, volume 50 cm^3, and a mobile scintillation detector with NaJ(Tl) crystal, ∅ 40mm x 40mm. The obtained experimental data are given in Table 2.

From the initial analysis [8] we have drawn a conclusion that the spin of the 589.9 keV upper state is $J^{\pi}=1/2$, but we have neglected the contribution to the coincidence number made by the second doublet member of E1 type from the state 3/2$^+$ 1/2 [600]. According to the estimations [6] the E1 gamma-transition intensity is 6 times weaker than the M1 transition intensity.

Now it is possible to do more accurate calculation based on the data of paper [13] dealing with α_k coefficient determination of the 346.9 keV transition (Table 1). In our calculations we proceeded from the fact that spins of the states 589.760, 242.935, 0 keV were already determined, being $3/2^+$, $3/2^-$ and $5/2^-$, respectively, multipolarity of the 242.935 transition is M1 and that of the 346.825 transition is E1. These are parameters to be determined:

1. The spin of the 589.968 keV state - either $1/2^-$ or $3/2^-$.
2. Possible E2 admixture to the M1 transition (δ^2) with E=346.933 keV.
3. Intensity ratio of M1 (+2) and E1 components of the 346.9 keV doublet transition.

A self-consistent solution must be achieved in case of proper correspondence between the relative intensity of gamma-rays, which discharge doublet states, and the value $\delta^2 = I_{\gamma}(E2)/(I_{\gamma}(M1)$, which characterizes E2 admixture in doublet transition, providing all these values are determined both through the internal conversion coefficient α_k and through the correlation coefficient A_{22}. Thus we get a two-equation system

$$\alpha_k^{exp}(346.9) = f\left[\frac{\alpha_k^{theor}(M1)}{1+\delta^2} + \frac{\delta^2}{1+\delta^2}\alpha_k^{theor}(E2)\right] + (1-f)\alpha_k^{theor}(E1), \qquad (1)$$

$$A_{22}^{exp}(346.9-242.9) = A_2(346.9)\cdot A_2(242.9) =$$

$$= \left[f\,\frac{F_2(LLJ_iJ) + (-1)^{L-L'}2\delta F_2(LL'J_iJ) + \delta^2F_2(L'L'J_iJ)}{1+\delta^2} + \right. \qquad (2)$$

$$\left. + (1-f)F_2(LLJ_iJ)\right]\cdot F_2(LLJ_fJ),$$

where

$\delta^2 = J_{\gamma}(E2)/J_{\gamma}(M1)$; $J_i \to J \to J_f$;

f is a relative intensity of gamma-rays of M1 (+E2) component, (1−f) is the E1 component intensity in an unresolved gamma-transition.

On analysing equation (2), we assign to the upper doublet state the spin value $3/2^-$ then $1/2^-$. In the latter case the coefficient F_2, which follows (1−f), has $J_i=3/2$, while in the first term of the equation F_2 has $J_i=1/2$.

On solving the system we find that:

1. The spin of the 589.914 keV state is $J^{\pi}=1/2$; it is seen in Fig.2, which presents the results of the graphical analysis.
2. Amplitude of E2 admixture to M1 in the 346.933 keV transition is $\delta=+0.086$ ($\delta^2=0.007$).
3. Intensity ratio of M1 and E1 gamma-rays in the 346.9 keV doublet is $I_{\gamma}(M1)/I_{\gamma}(E1) \approx 13 (f = 0.93)$.

Factor f for doublet transition with $E_{\gamma}=346.926$ keV being determined, we can specify energy difference of doublet states in the 590 keV region, i.e., ΔE. For this purpose we take the energy value $E_{eq.}=589.760$ keV (lower doublet state with $J^{\pi}=3/2^+$) as more reliable due to a greater number of cascades of accurately measured gamma-transitions. After calculating the energy of a doublet transition $E_0=346.825$ keV (transition 589.760 − 242.935 keV) and using the absolute energy value of the unresolved doublet transition $E_{\gamma}=346.926$ keV, we find ΔE from the expression

$$E_{\gamma} = f(E_0+\Delta E) + (1-f)E_0.$$

Taking into account the accuracy of E_γ and E_0 determination and the allowable values for f, we get

$\Delta E = (108 \pm 22)$ eV (Fig.3).

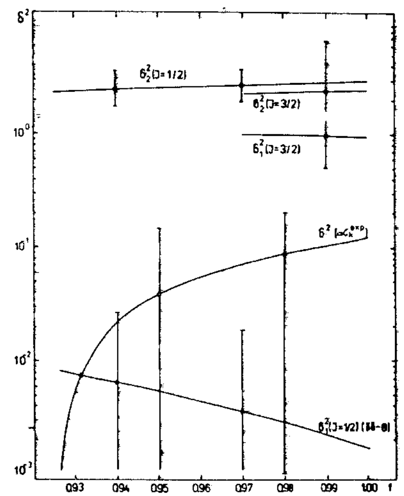

Fig.2. Parametrical diagram of δ^2 and f dependence for the 346.979 keV transition.

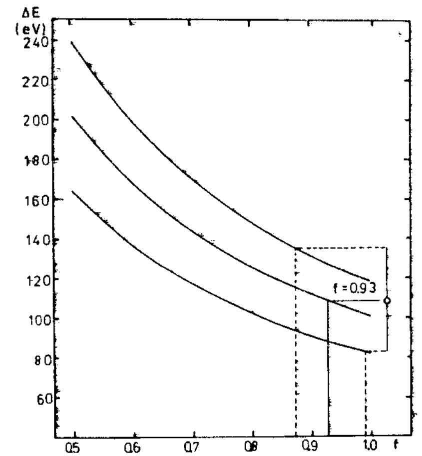

Fig.3. Energy difference between doublet states in ^{165}Er in the 590 keV region. (Dash-line show the region of parameter-allowable values).

This value is somewhat less than the earlier determined one /10/, it makes more precise the energy value of the upper doublet state

E=589.868 keV.

Having found the spin of this state, we may affirm that the 330.8 keV transition cannot have E2 multipolarity, it can be M1 only. Thus, in order to account for the a_k value of this transition, which is half as much as the theoretical a_k for M1 multipolarity, we must admit the existence of E1 doublet transition with the energy 108 eV higher than that of 330.8 keV M1 transition.

In this case through the equation

$$a_k^{exp}(330.8) = f a_k^{theor}(M1) + (1-f) a_k^{theor}(E1)$$

Table 3

Intensity ratio of gamma-rays and multipolarities of doublet transitions with ΔE of 150 eV or less

E_γ (keV)	$I_\gamma(M1)/I_\gamma(E1)$ /6/	/13/	Our paper	Multipolarity /6/	/11,13/	Our paper
156.100 156.208	–	–	0.66	E1	E2	E1 M1
330.777 330.885	–	–	0.77	M1	E2	M1 E1
346.825 346.933	5.7	2.2	13	–	(E1) M1	E1 M1+0.7% E2
513.627 513.735	–	–	3.0	M1	M1	E1 M1

we may find intensity ratio of doublet components

$I_\gamma(M1)/I_\gamma(E1) = 0.77.$

An intensive E1 transition with E=330.985 keV from the state $1/2^-\{510\}\uparrow + \{[512]\uparrow + Q_{22}\}$ to the state 589.760 keV proves that there is a considerable admixture of the [400]↑ component in this rotational state /3,6/.

We can determine more precisely the energy value E* of the $1/2^-$ state in the 920 keV region by means of just obtained (180 eV), the $3/2^+$ state energy E_0(589.760) and the unresolved transition energy E_γ(330.824 keV)

$$E^* = E_0 + E_\gamma + (1-f)\Delta E,$$

$$E^* = (920.645 \pm 0.019) \text{ keV}.$$

In the same way as with the transition with E_γ=330.824 keV we draw a conclusion on the doublet structure of the 156 and 514 keV transitions (Table 1). A similar structure can be attributed to 822 and 838 keV transitions, taking into account errors in measurements of a_k.

Table 3 shows the data characterizing doublet transitions in ^{165}Er. The finding of doublets with gamma-transitions of opposite parity and energy difference of 150 eV or less can present a certain interest. Therefore, it is necessary to continue investigations of gamma-gamma angular correlations of ^{165}Tm decay and improve accuracy in determining internal conversion coefficients in transitions connected with doublet states.

It should be noted that the experiments on studing the circular polarization asymmetry in doublet transitions occurring in ^{165}Tm $\to$ ^{165}Er decay may become a reference source for the investigation of proposses showing non-conservation of CP-invariance in electromagnetic interactions.

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Анализ свойств возбужденных состояний ^{165}Er

На примере распада ^{165}Tm показано, что анализ прецизионных измерений γ-лучей и коэффициентов внутренней конверсии вместе с коэффициентами угловых корреляций позволяет определить интенсивность и мультипольность γ-переходов, мало отличающихся по энергии. Определен спин состояния 589,868 кэВ как $1/2^-$. Обнаружены дублетные переходы разной четности с уровней: 1103,495; 929,645 и 745,968 кэВ на уровни в районе 590 кэВ, отличающиеся по энергии E=/108$\pm$22/ эВ.

Работа выполнена в Лаборатории ядерных проблем ОИЯИ.

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Analysis of ^{165}Er Excited State Properties

It is shown by the analysis of ^{165}Tm decay that the precision measurements of γ-ray and internal conversion electron intensities together with the measurements of angular correlation coefficients provide more data for the determination of γ-ray multipole composition and intensities of γ-transitions with small energy difference. The spin of the 589.868 keV state is found to be $I=1/2^-$. Doublet transitions of different parity from the states 1103.495, 920.645 and 745.968 keV to the levels of the 590 keV region with energy difference ΔE = =(108$\pm$22) eV are identified.

The investigation has been performed at the Laboratory of Nuclear Problems, JINR.

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