ELECTRICAL DIPOLE AND QUADRUPOLE TRANSITIONS IN EVEN-EVEN NUCLEI WITH QUADRUPOLE AND OCTUPOLE DEFORMATIONS

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Simple analytical expressions for the reduced probabilities of $E1$- and $E2$-transitions of deformable even-even nuclei with quadrupole and octupole deformations are obtained. The ratios of the reduced probabilities of $E1$- and $E2$-transitions for ^{104}Ru, ^{166}Er, ^{226}Ra, ^{238}U nuclei are calculated, and they are in satisfactory agreement with experimental data even for high spin-states.

Introduction

Atomic nuclei with quadrupole and octupole deformations have two rotational bands with opposite values of parity [1—5]. Energies of levels of these rotational bands, quadrupole and dipole transitions, magnitude of polarization-related electric dipole moment were studied for isotopes of barium, cerium, thorium, radium, actinium and several other nuclei [1—13]. In these nuclei, besides the main rotational band 0^+, 2^+, 4^+, ..., the band 1^-, 3^-, 5^-, ... with a projection of the spin on the axis of symmetry of a nucleus $K = 0$ was also observed.

The energy spectrum of an axial-symmetric nucleus with quadrupole and octupole deformations is calculated in [14] within the framework of phenomenological non-adiabatic collective theory. The carried out comparison of theoretical calculations of energy of the excited levels with experimental data for ^{162}Dy, ^{226}Ra, ^{232}Th, ^{232}U, ^{236}U, ^{238}U nuclei has shown that the offered model describes these data well, including levels with high spins.

The accounting of deformability of a nucleus, except for a change of the arrangement of energy levels, should affect the reduced probabilities of $E1$- and E2-transitions between the levels of even and odd bands. Therefore, the description of the reduced probabilities ofE1- and E2−transitions from the above-stated bands on the basis of phenomenological non-adiabatic collective theory is actual.

1. Wave Functions

The wave function of axisymmetric even-even nuclei with quadrupole and octupole deformations satisfies the Schrödinger equation [15]

$$-\sum_{\lambda=2,3}\frac{\hbar^2}{2B_\lambda}\frac{1}{\beta_\lambda^2}\frac{\partial}{\partial\beta_\lambda}\left(\beta_\lambda^2\frac{\partial\Psi_I^\pm(\beta_\lambda,\theta)}{\partial\beta_\lambda}\right)+$$

$$+\frac{\hbar^2 I(I+1)\Psi_I^\pm(\beta_\lambda,\theta)}{6(B_2\beta_2^2+B_3\beta_3^2)}+$$

$$+V(\beta_2,\beta_3)\Psi_I^\pm(\beta_\lambda,\theta)=E_I\Psi_I^\pm(\beta_\lambda,\theta), \quad (1)$$

where B_λ are mass parameters, I — spin of the even-even nucleus, V (β_2,β_3) — potential energy [14], and θ $=\{\theta_1,\theta_2,\theta_3\}$ — Euler's angles, and looks like

$$\Psi_I^\pm(\beta_2,\beta_3,\theta)=(\beta_2\beta_3)^{-1}F_I^\pm(\sigma)\chi_\nu(\varepsilon\mp\varepsilon_o)|IM0,\pm\rangle. \quad (2)$$

Here, the function $|\mathrm{IM}0,\pm\rangle$ describes rotations of an axisymmetric even-even nucleus with a projection of spin M on the Z, axis and $K = 0$, σ and ε are polar coordinates [10] which change in a region, where $0\le\sigma<\infty, -\frac{\pi}{2}\le\varepsilon\le\frac{\pi}{2}$,

$$\chi_\nu(\xi^\pm)=N_\varepsilon H_\nu(\xi^\pm)\exp\left[-\frac{1}{2}\left(\xi^\pm\right)^2\right], \quad (3)$$

where $\xi^\pm=\sqrt{B\omega_\varepsilon\left(\varepsilon\mp\varepsilon_0\right)/2}$, N_ε is a normalization coefficient, $H_\nu(\xi^\pm)$ — Hermite polynomial, ε_ν — the eigenvalues of the equation [10,11], ν=0, 1, 2, ..., and

$$F_I^\pm(x)=N_\sigma x^{S^\pm_{(I\nu)}}e^{-\frac{x}{2}}F(-p,2S^\pm_{(I\nu)}+1,x), \quad (4)$$

where N_σ is a normalization coefficient, $F(-p,$ $2S^\pm_{(I\nu)}+1,x)$ — degenerate hypergeometric function, $p = 0,1,2,\ldots$. Here, the designations [14] $g = \frac{BV_0\sigma_0^2}{\hbar^2}(S^\pm_{(I\nu)})^2=\frac{I(I+1)}{3}+2g\mp\frac{2B}{\hbar^2}\varepsilon_\nu, x=\frac{2\sqrt{-2B(E_I^\pm-V_0)}}{\hbar}\sigma$ are used.

2. Electric Dipole and Quadrupole Transitions

The reduced probabilities of $E2-$transitions between levels $|pI_i0\rangle$ and $\langle p'I_f0|$ are determined by the expressions

$$B(E2, I_i \to I_f) =$$
$$= B_a(E2, I_i \to I_f) S^2_{I_f I_i}(E2) \exp\left(-\hbar/2(BC_\varepsilon)^{1/2}\right), \quad (5)$$

$$B_a(E2, I_i \to I_f) = \frac{5}{16\pi} Q_0^2 (I_i 200/I_f 0)^2, \quad (6)$$

where $B_a(E2, I_i \to I_f)$ is the probability of $E2$-transition between the excited states of even-even nuclei in the adiabatic approach [16], and Q_0 — the internal quadrupole moment of a nucleus. The multiplier $S_{I_f I_i}$ takes into account the deformability of a nucleus and is determined as

$$S_{I_f I_i} \equiv \langle pI_f 0| \frac{\sigma}{\sigma_0} |p' I_i 0\rangle = \int\limits_0^\infty F^{\pm}_{I_f}(\sigma) \frac{\sigma}{\sigma_0} F^{\pm}_{I_i}(\sigma) d\sigma. \quad (7)$$

The general expression for matrix elements (7) is very a wkward. Therefore, we consider special cases. Let states $|pI_i0\rangle$ and $\langle p'I_f0|$ belong to the collective excited states of the main ($p = 0$) and the first rotational-β-vibrational bands ($p = 1$) with quadrupole and octupole deformations. Then, it is necessary to take p=0, 1 in formula (7).

Thus, assuming $p = 0, 1$ in the states of collective excitation, which are referred to the main and first rotational-β-vibrational bands with quadrupole and octupole deformations in wave function (2), we obtain the following formulas for calculation of the reduced probability of $E2$-transitions the even-even nuclei.

$$B(E2, I_i \to I_f) = \left[\frac{(2s_i+2)^2}{8g}\sqrt{\frac{1}{\Gamma(2s_f+2)\Gamma(2s_i+2)}}\times\right.$$
$$\left.\times\left(\frac{2s_i+2}{2s_f+2}\right)^{s_f}\left(\frac{2s_f+1}{s_i+s_f+1}\right)^{s_i+s_f+2}\right]^2\times$$
$$\times\Gamma^2(s_i+s_f+2)B_a(E2, I_i \to I_f)\exp\left(-\hbar/2(BC_\varepsilon)^{1/2}\right) (8)$$

are the probabilities of $E2$-transitions inside the main rotational-β-vibrational band with quadrupole and octupole deformations;

$$B(E2, I_i \to I_f) =$$
$$= \left[\frac{(2s_i+3)^2}{8g}\sqrt{\frac{2s_i+1}{(2s_i+3)\Gamma(2s_i+1)\Gamma(2s_f+2)}}\times\right.$$
$$\left.\times\left(\frac{2s_i+3}{2s_f+1}\right)^{s_f}\left(\frac{2s_f+1}{s_i+s_f+2}\right)^{s_i+s_f+2}\right]^2\times$$
$$\times\left(1-\frac{2s_f+1}{2s_i+2}\right)^2\Gamma^2(s_i+s_f+2)B_a(E2, I_i \to I_f)\times$$
$$\times\exp\left(-\hbar/2(BC_\varepsilon)^{1/2}\right) \quad (9)$$

the probabilities of $E2$-transitions between the main and first rotational-β-vibrational bands with quadrupole and octupole deformations;

$$B(E2, I_i \to I_f) =$$
$$= \left[\frac{(2s_i+3)^2}{8g}\left(\frac{2s_i+3}{2s_f+3}\right)^{s_f}\left(\frac{2s_f+3}{s_i+s_f+3}\right)^{s_i+s_f+2}\right]^2\times$$
$$\times\left(1-\frac{(2s_f+3)(s_f+1)+(2s_i+3)(s_i+1)}{2(s_i+1)(s_f+1)}\times\right.$$
$$\left.\times\frac{s_i+s_f+2}{s_i+s_f+3}+\frac{(2s_i+3)(2s_f+3)(s_i+s_f+2)}{4(s_i+1)(s_f+1)(s_i+s_f+3)}\right)^2\times$$
$$\times\frac{(2s_i+1)(2s_f+1)\Gamma^2(s_i+s_f+2)}{(2s_i+3)(2s_f+3)\Gamma(2s_i+1)\Gamma(2s_f+1)}\times$$
$$\times B_a(E2, I_i \to I_f)\exp\left(-\hbar/2(BC_\varepsilon)^{1/2}\right) \quad (10)$$

— the probabilities of $E2$-transitions inside the first rotational-β-vibrational band with quadrupole and octupole deformations.

The reduced probabilities of electric dipole transitions between the levels $|pI_i0\rangle$ and $\langle p'I_f0|$ with opposite parities are defined as

$$B(E1, I_i \to I_f) = B_a(E1, I_i \to I_f) S^2_{I_f I_i}\exp\left(-\frac{2\hbar}{\sqrt{BC_\varepsilon}}\right), \quad (11)$$

where

$$B_a(E1, I_i \to I_f) = \frac{3}{4\pi} D_0^2 (I_i 100/I_f 0)^2 \quad (12)$$

are the probabilities of $E1$-transitions between excited states of even-even nuclei in the adiabatic approximation [16]. Here, $D_0 = \frac{9AZe^3}{56\pi\sqrt{35}}\left(\frac{1}{J} + \frac{15}{8QA^{1/3}}\right)\beta_2^0\beta_3^0$ is the polarization-related electric dipole moment [9], and

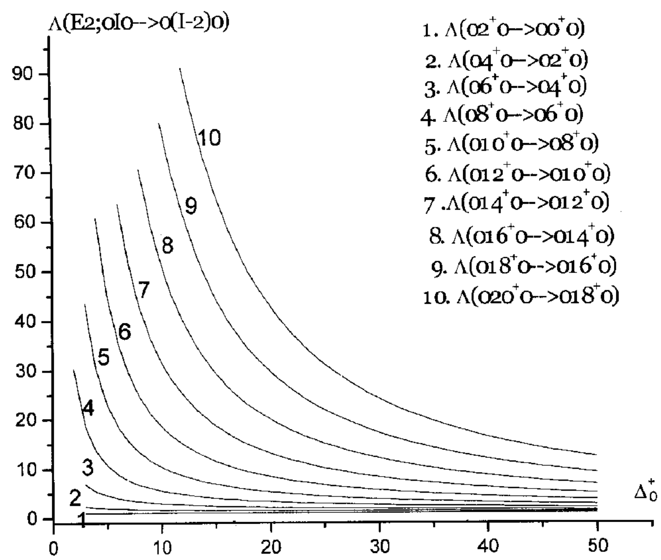

Fig. 1. Dependences of the ratios of the reduced probabilities of $E2$-transitions between the energy levels of positive parity to the reduced probability of $E2$-transition from the state of the first excited level with spin 2^+ to the ground state on the parameter Δ_0^+

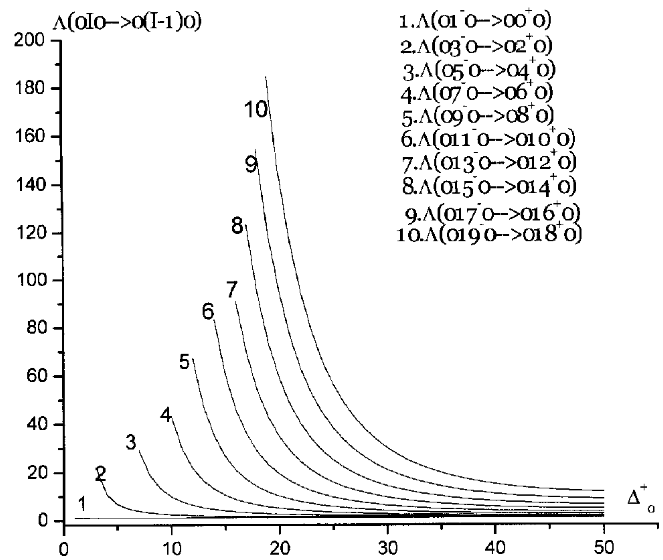

Fig. 2. Dependence of the ratios of the reduced probabilities of $E1$-transitions between the energy levels of negative and positive parity to the reduced probability of $E1$-transition from the state of the excited level with spin 1^- to the ground state on the parameter Δ_0^+ at the fixed parameter $\Delta_0^- = 50$

$S_{I_i I_f}(E1)$ is the factor conditioned by quadrupole and octupole deformations of the nucleus surface,

$$S_{I_f I_i} \equiv \langle pI_f 0\Big|\frac{\sigma^2}{\sigma_0^2}\Big|p' I_i 0\rangle = \int\limits_0^\infty F_{I_f}^{\pm}(\sigma)\frac{\sigma^2}{\sigma_0^2}F_{I_i}(\sigma)d\sigma. \quad (13)$$

By analyzing partial cases, like the case of $E2$-transitions, we get the following formulas for the calculation of the reduced probability of electric dipole transitions in even-even nuclei:

$$B(E1, I_i \to I_f) =$$

$$= \left\{ \frac{(2s_i+3)^3}{64g^2}\left(\frac{2s_i+1}{2s_f+2}\right)^{s_f}\left(\frac{2s_f+1}{s_i+s_f+1}\right)^{s_i+s_f+3} \times \right.$$

$$\left. \times \frac{\Gamma(s_i+s_f+3)}{\sqrt{\Gamma(2s_f+2)\Gamma(2s_i+2)}}\right\}^2 \times$$

$$\times B_a(E1, I_i \to I_f)\exp\left(-\frac{2\hbar}{\sqrt{BC_\varepsilon}}\right) \quad (14)$$

are the probabilities of $E1$-transitions between the levels of the octupole and main rotational-β-vibrational bands with quadrupole and octupole deformations, where $s_f^2 = \frac{I(I-1)}{3} + \Delta_0^+ s_i^2 = \frac{I(I+1)}{3} + \Delta_0^-$;

$$B(E1, I_i \to I_f) =$$

$$= \left\{ \frac{(2s_i+3)^3}{64g^2}\left(\frac{2s_i+3}{2s_f+2}\right)^{s_f}\left(\frac{2s_f+1}{s_i+s_f+2}\right)^{s_i+s_f+3} \times \right.$$

$$\left. \times \frac{\sqrt{2s_i+1}\Gamma(s_i+s_f+3)}{\sqrt{(2s_i+3)\Gamma(2s_i+1)\Gamma(2s_f+2)}}\right\}^2 \times$$

$$\times \left(1 - \frac{(2s_f+1)(s_i+s_f+3)}{(2s_i+2)(s_i+s_f+2)}\right) \times$$

$$\times B_a(E1, I_i \to I_f)\exp\left(-\frac{2\hbar}{\sqrt{BC_\varepsilon}}\right) \quad (15)$$

— the probabilities of $E1$-transitions between the levels of the first rotational-β-vibrational band with quadrupole and octupole deformations, where $s_f^2 = \frac{I(I-1)}{3} + \Delta_0^-$ and $s_i^2 = \frac{I(I+1)}{3} + \Delta_0^+$.

It is convenient to consider the ratios of the reduced probabilities of $E1$- and $E2$-transitions to the reduced probability of EL-transitions from the states of the first quadrupole and dipole excitations ($L = 2$ for quadrupole transitions and $L = 1$ for dipole ones) to the ground state:

$$\Lambda(EL, I_i \to I_f) = \frac{B(EL, I_i \to I_f)}{B(EL, L \to 0)}. \quad (16)$$

T a b l e 1. Theoretical and experimental values of the ratios of the reduced probabilities of *E*2-transitions

Nucleus and parameters	$E2$-transitions	Theory	Experiment
^{104}Ru	$02^+0\to00^+0/02^+0\to00^+0$	1	1
$\Delta_0^+=40.0$	$04^+0\to02^+0/02^+0\to00^+0$	1.34	1.3(6)
$\Delta_0^-=161.24$	$06^+0\to04^+0/02^+0\to00^+0$	1.72	2.2(6)
[17]	$08^+0\to06^+0/02^+0\to00^+0$	2.28	2.2(2)
	$010^+0\to08^+0/02^+0\to00^+0$	3.14	2.1(6)
	$05^-0\to03^-0/02^+0\to00^+0$	0.80	0.79(8)
^{166}Er	$02^+0\to00^+0/02^+0\to00^+0$	1	1
$\Delta_0^+=27.0$	$04^+0\to02^+0/02^+0\to00^+0$	1.4	1.4(1)
[17]	$06^+0\to04^+0/04^+0\to02^+0$	1.37	0.9(3)
	$010^+0\to08^+0/08^+0\to06^+0$	1.49	1.2(1)
	$010^+0\to08^+0/08^+0\to06^+0$	1.49	1.1(1)
	$012^+0\to010^+0/010^+0\to08^+0$	1.51	1.0(1)
	$012^+0\to010^+0/010^+0\to08^+0$	1.51	1.9(1)
^{226}Ra	$00^+0\to02^+0/00^+0\to02^+0$	1	$1.000^{+0.009}_{-0.009}$
$\Delta_0^+=400.0$	$02^+0\to04^+0/00^+0\to02^+0$	0.437	$0.874^{+0.008}_{-0.009}$
[16]	$04^+0\to06^+0/00^+0\to02^+0$	0.378	$0.536^{+0.005}_{-0.005}$
	$06^+0\to08^+0/00^+0\to02^+0$	0.364	$0.468^{+0.004}_{-0.004}$
	$08^+0\to010^+0/00^+0\to02^+0$	0.366	$0.507^{+0.005}_{-0.005}$
	$010^+0\to012^+0/00^+0\to02^+0$	0.377	$0.295^{+0.003}_{-0.003}$
	$012^+0\to014^+0/00^+0\to02^+0$	0.396	$0.441^{+0.004}_{-0.004}$
	$014^+0\to016^+0/00^+0\to02^+0$	0.421	$0.388^{+0.003}_{-0.004}$
	$016^+0\to018^+0/00^+0\to02^+0$	0.453	$0.402^{+0.004}_{-0.004}$
	$018^+0\to020^+0/00^+0\to02^+0$	0.491	$0.472^{+0.005}_{-0.009}$
	$020^+0\to022^+0/00^+0\to02^+0$	0.536	$0.755^{+0.007}_{-0.008}$
	$022^+0\to024^+0/00^+0\to02^+0$	0.589	$0.851^{+0.018}_{-0.012}$
	$024^+0\to026^+0/00^+0\to02^+0$	0.650	$0.420^{+0.006}_{-0.004}$
	$026^+0\to028^+0/00^+0\to02^+0$	0.720	$0.682^{+0.071}_{-0.041}$
	$028^+0\to030^+0/00^+0\to02^+0$	0.800	$0.455^{+0.028}_{-0.007}$
	$032^+0\to034^+0/00^+0\to02^+0$	0.890	$0.185^{+0.005}_{-0.004}$
^{238}U	$00^+0\to02^+0/00^+0\to02^+0$	1	1
$\Delta_0^+=400.0$	$06^+0\to08^+0/00^+0\to02^+0$	0.36	0.40(6)
[17]	$010^+0\to012^+0/00^+0\to02^+0$	0.38	0.44(6)
	$012^+0\to014^+0/00^+0\to02^+0$	0.40	0.44(5)
	$014^+0\to016^+0/00^+0\to02^+0$	0.42	0.43(4)
	$016^+0\to018^+0/00^+0\to02^+0$	0.45	0.34(6)
	$018^+0\to020^+0/00^+0\to02^+0$	0.49	0.38(6)
	$020^+0\to022^+0/00^+0\to02^+0$	0.54	0.33(6)
	$022^+0\to024^+0/00^+0\to02^+0$	0.59	0.44(4)
	$024^+0\to026^+0/00^+0\to02^+0$	0.65	0.48(2)
	$026^+0\to028^+0/00^+0\to02^+0$	0.72	0.44(2)

The ratio of the reduced probabilities of$E2$-transitions between the energy levels of the same parity is determined by the parameter Δ_0^+ for the even band and by Δ_0^- for the odd band. But the ratio of the reduced probabilities of$E1$-transitions between the energy levels of different parities is determined by the parameters Δ_0^+ and Δ_0^-.

In Figs. 1, 2, the ratios of reduced probabilities of $E1$- and $E2$-transitions vs the parameter Δ_0^+ are shown. For $E1$-transitions, we fix $\Delta_0^-=50$.

T a b l e 2. Theoretical and experimental values of the ratios of reduced probabilities of *E*1-transitions

Nucleus and parameters	$E1$-transitions	Theory	Experiment
^{226}Ra	$00^+0\to01^-0/00^+0\to01^-0$	1.000	$1.000^{+0.392}_{-0.392}$
$\Delta_0^+=200.0$	$02^+0\to03^-0/00^+0\to01^-0$	0.546	$0.617^{+0.235}_{-0.235}$
$\Delta_0^-=190.$	$04^+0\to05^-0/00^+0\to01^-0$	0.526	$0.298^{+0.111}_{-0.111}$
[16]	$06^+0\to07^-0/00^+0\to01^-0$	0.558	$0.186^{+0.068}_{-0.068}$
	$08^+0\to09^-0/00^+0\to01^-0$	0.624	$0.384^{+0.141}_{-0.141}$
	$012^+0\to013^-0/00^+0\to01^-0$	0.863	$0.758^{+0.276}_{-0.276}$
	$014^+0\to015^-0/00^+0\to01^-0$	1.051	$1.176^{+0.594}_{-0.594}$
	$016^+0\to017^-0/00^+0\to01^-0$	1.302	$1.355^{+0.497}_{-0.497}$
	$018^+0\to019^-0/00^+0\to01^-0$	1.630	$1.535^{+0.605}_{-0.605}$
	$020^+0\to021^-0/00^+0\to01^-0$	2.056	$2.074^{+0.777}_{-0.777}$
	$022^+0\to023^-0/00^+0\to01^-0$	2.606	$2.130^{+0.878}_{-0.878}$
	$024^+0\to025^-0/00^+0\to01^-0$	3.308	$6.350^{+2.389}_{-2.389}$
	$026^+0\to027^-0/00^+0\to01^-0$	4.206	$6.259^{+2.587}_{-2.290}$
	$030^+0\to031^-0/00^+0\to01^-0$	6.760	$3.903^{+1.468}_{-1.658}$

It is seen from Figs. 1, 2 that the ratios of the reduced probabilities of$E1$- and $E2$-transitions decrease with different rates with increase in parameterΔ_0^+. At a fixed value of the parameter Δ_0^+, the ratios of the reduced probabilities of these transitions increase with the spin of levels of a nucleus.

In Tables 1, 2, the comparison of theoretical and experimental values of the ratios of reduced probabilities of $E2$- and $E1$-transitions is carried out for ^{104}Ru, ^{166}Er, ^{226}Ra, and ^{238}U nuclei at several values of the parameters Δ_0^+ and Δ_0^-. It is seen from Tab. 1, 2, that the given theory describes the ratios of the reduced probabilities satisfactorily.

Conclusion

Thus, a simple consideration of the reduced probabilities of $E1$- and $E2$-transitions of the even-even nuclei with quadrupole and octupole deformations with regard for a change of the shape of a nucleus at the excitation is offered in the present paper, and analytical expressions for these quantities are obtained. The ratios of the reduced probabilities of $E1$- and $E2$-transitions are determined by two parameters Δ_ν^+ and Δ_ν^- and are different for even and odd bands. For all the nuclei, we have $\Delta_\nu^+ < \Delta_\nu^-$, which is connected to the presence of a tunnel transition between the shapes of the nuclei with opposite values of the octupole deformation.

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ЕЛЕКТРИЧНІ ДИПОЛЬНІ І КВАДРУПОЛЬНІ ПЕРЕХОДИ В ПАРНО-ПАРНИХ ЯДРАХ З КВАДРУПОЛЬНОЮ І ОКТУПОЛЬНОЮ ДЕФОРМАЦІЯМИ

Ш. Шаріпов, М.С. Надирбеков

Р е з ю м е

Отримано прості аналітичні вирази для зведених імовірностей $E1$- та $E2$-переходів у деформованих парно-парних ядрах з квадрупольною і октупольною деформаціями. Обчислено значення вказаних імовірностей для ядер ^{104}Ru, ^{166}Er, ^{226}Ra, ^{238}U. Результати обчислень задовільно узгоджуються з експериментальними даними, в тому числі для станів з великими спінами.