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ЯДРА

REACTION $(n, \gamma\alpha)$ ASSISTED BY INTERNAL AND RESONANCE CONVERSION

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We consider spectra of γ, internal conversion and α transitions in (n, γ) and $(n, \gamma\alpha)$ reactions on $^{143}_{60}$Nd. Probabilities of mixing of neutron resonances with different spins and parities arising due to internal and resonance conversion are also considered from the point of view of studying the P-violating processes. Arguments are presented in favor of that the α decay of the 55-eV neutron resonance 4^- to the ground state, observed earlier, may be due to such interaction.

1. INTRODUCTION

The intriguing effects were detected at JINR in the consecutive studies of the reaction (n, α) on the rare-earth nuclei of $^{143}_{60}$Nd and $^{147}_{62}$Sm. Experiments conducted by Popov *et al.* [1] with the ^{147}Sm target revealed the anomalously large α widths of neutron resonances 4^-, which exceeded those of the 3^- resonances. This is in spite of the fact that the α transitions from the 4^- resonances to the ground nuclear state 0^+ are forbidden by conservation of parity. Therefore, the result may be attributed to violation of space parity at the level of 100%. On the other hand, similar effects were observed in paper [2] by Andrejewski *et al.*, where the reaction $^{143}_{60}$Nd$(n, \gamma\alpha)$ was studied. In these experiments, however, the γ quanta themselves are not detected. Instead, the α-particle spectrum is determined. Then the emission of a γ quantum is concluded in the case of missing energy particle. In such an approach, with the resolution of α detectors of at least tens kiloelectronvolts, a question of the presence of the radiative transitions with smaller energies remains open. The radiative transition probabilities are proportional to ω^3, ω being the transition energy. As a result, actually, the transitions with the energies of several megaelectronvolts turn out to be most probable ones. They dominate in the spectrum, and may be easily observed by the α detector. Moreover, the internal conversion (IC) processes were actually ignored. At the same time, just in the case of relatively small transition energies $\omega \lesssim 200$ keV, allowance for the IC transitions is very important. Moreover, the IC rate does not vanish at the threshold, especially in the case of the $M1$ transitions [3–5]. In contrast, as one can see in Fig. 3 below, they reach 5 to 6 orders of magnitude at this energy. We recall that the particular role of the $M1$ low-energy transitions between the compound nuclear states was noted in [6, 7]. Therefore, they can be expected to give an important contribution to the interaction of neighbor compound nuclear states. Furthermore, below the threshold of IC, there is onset of discrete, or resonance conversion (RC), which may be even stronger than traditional IC [4]. In RC, the nuclear energy can be transferred to an atomic electron which is lifted up to a discrete level.

Such a situation seems to have been observed in [2] in the reaction of ^{143}Nd(n, α) introduced by the resonance neutrons. In the α-particle spectrum, certain peaks were detected which were associated with α decay of the 55-eV resonance 4^- to the ground state 0^+ of ^{140}Ce. Below we analyze a possibility of the situation. The effect may be due to low-energy transitions between the compound states which, we will see, are strongly accelerated as compared to the radiative transitions by either traditional or resonance IC. If the energy of such transitions is smaller than the energy resolution of the α detector, they may appear as direct transitions to the ground state. Note that the resonance electron transitions with the energies of a few electronvolts may be found practically in any atom [8]. This is either due to a high level density in a nucleus ($\sim$200 per kiloelectronvolt) in the case of RC in the valence shell, or due to large widths of atomic levels (tens electronvolts) in the case of the hole in the atomic K shell.

We consider the RC factors along with internal conversion coefficients (ICC) for the compound–compound nuclear transitions, particularly for the transitions with very low energies of a few electronvolts, which can be in a resonance with the

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electron transitions in the P and Q shells of the atom. It is worthy of noting that still Wigner, and later Lyuboshitz *et al.* [9] pointed out the possibility of interaction of nuclear states, including those with different spins and parities, via the electron shell. The effect was found experimentally in muonic atoms [5, 10]. Furthermore, the resonance effect of mixing of the $3/2^+$ and $5/2^+$ nuclear levels due to hyperfine interaction in the hydrogen-like ions of ^{229}Th was predicted in [11].

2. OUTLINE OF THE MODEL: ELECTROMAGNETIC WIDTHS IN THE REACTION (n, γ)

Consider a compound nucleus formed by a resonance neutron. Its excitation energy may be expressed as

$$E_1 = S_n + E_n, \quad (1)$$

where S_n is the neutron separation energy, and E_n is the kinetic energy of the incoming neutron. In Fig. 1, we present the calculated evaporation spectrum of γ quanta from the nucleus of $^{144}_{60}$Nd, $S_n = 7.81702$ MeV, with the excitation energy $E_1 = 7.817075$ MeV (the 55-eV 4^- resonance on ^{143}Nd). Calculation of the probabilities of the radiative transitions between the compound nuclear states always remains a challenging problem (e.g., [6, 12]). We will only deal with the radiative spectra. To this end, the probability of the radiative transition may be assumed to be proportional to ω^3 as follows:

$$\frac{dP_\gamma}{d\omega} = f\omega^3\rho(E_1 - \omega), \quad (2)$$

where the nuclear level density $\rho(E)$ may be taken according to [7]:

$$\rho(E) = \exp(\sqrt{aE}) \quad (3)$$

with the level density constant $a = A/8$ MeV^{-1}, A being the mass number. Respectively, the probability of a radiative transition with the energy $\omega_k = E_1 - E_k$ to a specific final state of a nucleus k with the energy E_k has the form

$$P_\gamma^{(k)} = f\omega_k^3. \quad (4)$$

The constant f in Eqs. (2) and (4) is determined from a normalization condition. For the calculation of the radiative spectrum, we will normalize the total transition probability P_γ

$$P_\gamma = \int_0^{E_1} \frac{d\,P_\gamma(\omega)}{d\omega}\rho(E_1 - \omega)d\omega \quad (5)$$

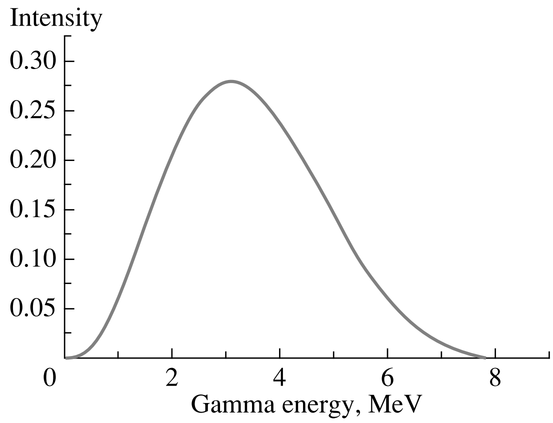

Fig. 1. Theoretical γ-quantum spectrum of transitions from the 55-eV neutron resonance in the nucleus ^{144}Nd.

at unity as follows:

$$f = \left[\int_0^{E_1} \omega^3\rho(E_1 - \omega)d\omega\right]^{-1}. \quad (6)$$

One may also normalize it at the absolute probability of an electromagnetic transition for example, by making use of the experimental radiative width of the neutron resonance.

The shape of the radiative spectrum in Fig. 1 does not change with the allowance for the IC channel. However, the resulting probability of soft electromagnetic transitions becomes essentially higher due to large values of ICC near the threshold, in accordance with what is said in the Introduction. For the IC channel, the expressions (2) and (4) should be multiplied by the total ICC $\alpha_{\rm tot}^{\tau L}(\omega)$ or $\alpha_{\rm tot}^{\tau L}(\omega_k)$, respectively, where τL are the type and the multipole order of the transition. Moreover, with allowance for the IC channel, the total probability of the electromagnetic transitions, both radiative and IC ones could be normalized at unity. Instead, we will keep normalization (6) throughout the paper, relying on the fact of nonvariance of the shape of the radiative spectrum (2). Then the relative total radiation and IC probability will be

$$P_c^{(\rm tot)} = \left\{\int_I^{E_1} [1 + \alpha^{\tau L}(\omega)]\omega^3\rho(E_1 - \omega)\,d\omega\right\}^{-1}, \quad (7)$$

I being the ionization potential of the atom.

Furthermore, the RC transitions between certain atomic shells take the place of the traditional IC at the corresponding energies of the nuclear transitions. The partial RC widths are obtained from the radiative ones by multiplying by the RC factor R. Their relative contribution to the total electromagnetic width reads as follows:

$$P_{\mathrm{RC}}^{(\mathrm{tot})} = \sum_k R^{(\tau L)}(\omega_k) P_\gamma^{(k)} = \tag{8}$$
$$= f \sum_k R^{(\tau L)}(\omega_k)\omega_k^3.$$

In finer details, the role of the low energy RC transitions is considered in Section 5.

3. REACTION $(n, \gamma\alpha)$

Let us define the probability of the $(\gamma\alpha)$ decay of a compound nucleus to the ground state, accompanied with emission of a gamma quantum with the energy ω and the α particle with the energy $E_1 - \omega + Q_\alpha$ as follows:

$$\frac{dP_{\gamma\alpha}(\omega)}{d\omega} = f_\alpha \frac{dP_\gamma(\omega)}{d\omega} P_\alpha(E_1 - \omega + Q_\alpha), \tag{9}$$

where Q_α is the Q value, $P_\alpha(E_\alpha)$ is the probability of the α decay with the energy E_α, and f_α is the normalization constant. For the α decay to the ground state, $P_\alpha(E_\alpha)$ is given by the branching ratio as follows:

$$P_\alpha(E_\alpha) = \Gamma_\alpha(E_\alpha)/\Gamma_{\mathrm{all}}(E_i). \tag{10}$$

In Eq. (10), for the α decay width to the ground state, one can put down essentially the following expression (e.g., [13]):

$$\Gamma_\alpha(E_\alpha) = \rho(E_i)^{-1}\exp(-S(E_\alpha)) \tag{11}$$

with the action

$$S = \int_{r_1}^{r_2} \sqrt{2m_\alpha(V(r) - E_\alpha)}dr, \tag{12}$$

where $\rho(E_i)$ is the nuclear level density in the initial state, m_α is the α-particle mass, $V(r)$ is the potential energy of interaction of the α particle with the nucleus, and r_1, r_2 are the classical turning points. Furthermore, $\Gamma_{\mathrm{all}}(E_i)$ is the total radiative width of the initial state. According to (2) and similar to (11), the latter can be expressed as follows:

$$\Gamma_{\mathrm{all}}(E_i) = \int_0^{E_i} f\, \frac{\rho(E_i - \omega)}{\rho(E_i)}\, \omega^3 d\omega. \tag{13}$$

Substituting (10)–(13) into (9), one arrives at the following expression for the radiative spectrum in the $(n, \gamma\alpha)$ reaction:

$$\frac{dP_{\gamma\alpha}(\omega)}{d\omega} = f_\alpha \omega^3 \rho(E_1 - \omega) e^{-S(E_1 - \omega + Q_\alpha)} \Big/ \int_0^{E_1 - \omega} x^3 \rho(E_1 - \omega - x) dx. \tag{14}$$

Similar to Eqs. (6) and (7), the total probability of the (γ, α) transitions may be normalized at unity:

$$f_\alpha = \left\{ \int_0^{E_1} \frac{dP_\gamma(\omega)}{d\omega} P_\alpha(E_1 - \omega + Q_\alpha) d\omega \right\}^{-1}. \tag{15}$$

Respectively, the probability of the (γ, α) transition to the ground state through a specific nuclear state k with the energy E_k and the transition energy $\omega_k = E_1 - E_k$ may be written as

$$P_{\gamma\alpha}^{(k)} = f_\alpha P_\gamma^{(k)}(\omega_k) P_\alpha(E_1 - \omega_k + Q_\alpha). \tag{16}$$

Furthermore, the relative probability of the RC transition followed by the α transition will be

$$P_{c\alpha}^{(k)} = f_\alpha P_c^{(k)} P_\alpha(E_1 - \omega_k + Q_\alpha), \tag{17}$$

where $P_c^{(k)}$ is the probability of the RC transition. Numerical calculations are performed in Sections 4, 5.

4. RESULTS OF CALCULATION

4.1. *Radiative and α Spectra*

The spectrum of the "primary" γ quanta calculated by means of (2), (6) is presented in Fig. 1. As one can see from Fig. 1, maximum of the spectrum is at approximately 3 MeV. In Fig. 2, we present the photon spectrum in the (γ, α) decay of the compound $^{144}_{60}$Nd nucleus, calculated by means of (9), (15). Emission of the α particles occurs after emission of the photons. Therefore, the emission of the α particles does not affect the probability of emitting the "primary" quanta. Nevertheless, the spectrum in Fig. 2 is different from that in Fig. 1. As the tunneling

Table 1. Percentages of the radiative transitions $N_\gamma^<(\omega_{\max})$ and both the radiative and internal conversion transitions electromagnetic widths $N_t^<(\omega_n)$, with the transition energy $\omega < \omega_{\max}$, in the reaction (n,γ), in comparison with the percentages of the electromagnetic transitions $N_{t\alpha}^<(\omega_{\max})$ in the reaction $(n,\gamma\alpha)$

$\omega_{\max}$, keV	$N_\gamma^<(\omega_{\max})$	$E1$		$M1$	
		$N_t^<(\omega_{\max})$	$N_{t\alpha}^<(\omega_{\max})$	$N_t^<(\omega_{\max})$	$N_{t\alpha}^<(\omega_{\max})$
500	1.52×10^{-3}	1.53×10^{-3}	1.47×10^{-2}	1.60×10^{-3}	1.53×10^{-2}
100	3.10×10^{-6}	4.85×10^{-6}	5.70×10^{-5}	1.33×10^{-5}	1.57×10^{-4}
50	2.00×10^{-7}	5.39×10^{-7}	6.48×10^{-6}	2.38×10^{-6}	2.86×10^{-5}
30	2.62×10^{-8}	1.16×10^{-7}	1.41×10^{-7}	6.27×10^{-7}	7.72×10^{-6}

probabilities of the α particle through the barrier strongly increase with its energy, the maximum of the curve in Fig. 2 becomes sharper. It also shifts considerably towards the softer energies, from 2.5 to 1.5 MeV.

4.2. Internal Conversion

The total ICC values for the low-energy $M1$ and $E1$ transitions are plotted in Fig. 3. The IC threshold, which is equal to the ionization potential of the valence shell, begins at about 7 eV for the atoms of $^{144}_{60}$Nd. At the threshold, the ICC values reach 10^7 and 10^6 for the $M1$ and $E1$ transitions, respectively, and fall down with the energy. They become of the order of unity at the energies of approximately 100 keV.

In spite of such big ICC at the threshold, the integral contribution of IC (7) turns out to be of the order of 10^{-3}. However, at low transition energies the probability of IC is considerable. In Table 1, we present the relative probabilities of the electromagnetic decay for the $E1$ and $M1$ transitions with the energies $\omega \le \omega_{\max}$ for various $\omega_{\max}$. In the reaction $(n,\gamma\alpha)$, these percentages are of the order of 10^{-2} for $\omega_{\max} = 500$ keV, and rapidly decrease with decreasing $\omega_{\max}$. Again, the listed probabilities in the reaction $(n,\gamma\alpha)$ turn out to be much higher than the probabilities of the corresponding "primary" transitions in the (n,γ) reaction. As it should be expected, taking the IC into account raises the relative probability of the electromagnetic decay in the $(n,\gamma\alpha)$ reaction by an order of magnitude.

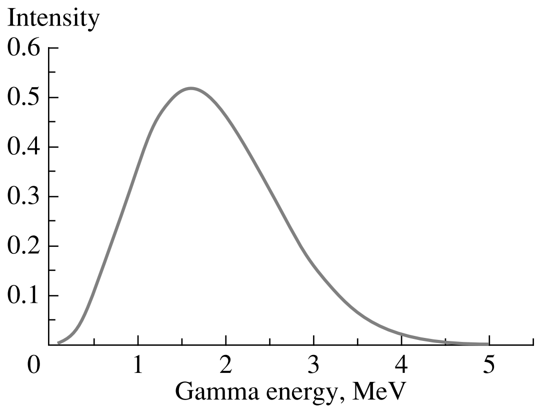

Fig. 2. Calculated γ-quantum spectrum in the reaction $^{143}_{60}$Nd $(n,\gamma\alpha)$ $^{140}_{58}$Ce.

5. CALCULATION OF RESONANCE CONVERSION FACTORS FOR LOW-ENERGY TRANSITIONS

Theory of resonance conversion is presented, e.g., in [4, 5, 11, 14, 15]. The RC factor R is defined as the ratio of probabilities of discrete conversion Γ_c and

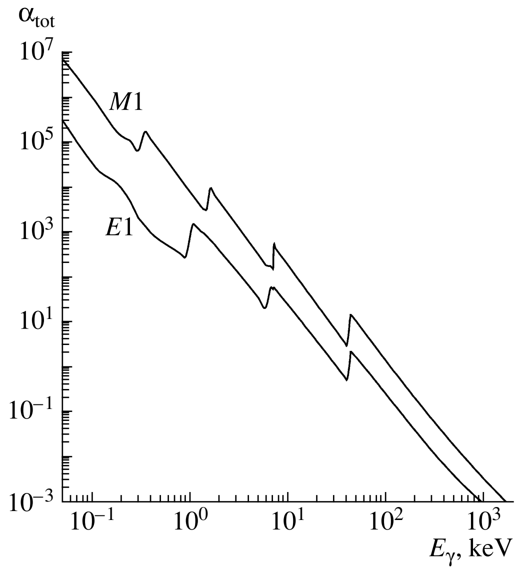

Fig. 3. The total ICC values $\alpha_{\rm tot}$ for the $E1$ and $M1$ transitions versus the transition energy E_γ for the atom of ^{144}Nd.

Table 2. Resonance conversion characteristic values for a representative nucleus of ^{148}Sm (E_n is the transition energy)

Transition	Multipolarity	E_n, eV	α_d, eV	Γ, eV	R	Γ_i/Γ_0
$1s \to 6p_{3/2}$	$E1$	46832	4.69	0.49	9.5	10^{-4}
$1s \to 7s$	$M1$	46830	11.97	0.032	375	10^{-4}
$6s \to 6p_{3/2}$	$E1$	1.6	2.6×10^9	0.03	0.9×10^{11}	10^{-18}
$6s \to 7s$	$M1$	2.8	2.7×10^9	0.03	0.9×10^{11}	10^{-17}

emission of a photon by the nucleus Γ_γ. In the vicinity of a resonance transition, it is given by the following expression:

$$R = \frac{\Gamma_c}{\Gamma_\gamma} = \frac{\alpha_d \Gamma}{2\pi[\Delta^2 + (\Gamma/2)^2]}. \quad (18)$$

This expression for the R factor has to be used in Eq. (8). In (18), α_d is the resonance analog of the traditional ICC, Δ is the resonance defect of the atomic and nuclear transitions: $\Delta = E_a - E_n$, with E_a and E_n being the atomic and nuclear transition energies. Furthermore, Γ is the total width of the atomic and nuclear levels in the initial and final states. This width is $\sim 10^{-2}$ eV for the neutron resonances plus the atomic width Γ_a. The latter depends drastically on the number of the electron shell. For the K shell, Γ_a reaches several tens of electronvolts. For the upper shells, it depends on the shell principal quantum number n as well as the energy $E_a^{(n)}$ as follows:

$$\Gamma_a = \frac{[E_a^{(n)}]^3}{n^3}, \quad (19)$$

that is essentially proportional to the transition energy in cube, in accordance with (2), and inversely proportional to n^3. For example, $\Gamma \approx 10^{-8}$ eV for the transitions involving the ground state of an atom and one of its excited levels with the energy of the order of electronvolts. In the case of the exact resonance, the expression for R which is responsible for the contribution of the discrete conversion into the electromagnetic transition probability, acquires the following form

$$R = \frac{2\alpha_d}{\pi \Gamma}. \quad (20)$$

For the present purposes of assessing the role of the soft electromagnetic transitions in the $(n, \gamma\alpha)$ reaction on $^{143}_{60}$Nd, we can use the resonance conversion coefficients α_d for transitions in the neighboring representative nucleus of ^{148}Sm which are calculated in [8]. These transitions are in resonance with the electron transitions $1s \to 6p_{3/2}$ and $6s \to 6p_{3/2}$ ($E1$ transitions), as well as $1s \to 7s$ and $6s \to 7s$ ($M1$ transitions). Note that the conversion $M1$ transitions are the strongest if they occur between the s states, while radiative transitions between these states are strongly prohibited. The lowest levels in the P shell with the subshell states $6s_{1/2}$ and $6p_{3/2}$ with the energies of 4.7 and 3.2 eV, respectively, were considered. Calculations were performed within the framework of the Dirac–Fock method with regard for the finite nuclear size as well as the highest quantum-electrodynamic corrections including the vacuum polarization and the electron self-energy [16]. The atomic level widths were obtained using the known value $\Gamma = 52$ eV [17] for the transition between the L_2 and K atomic shells. For the other shells, it was calculated by means of Eq. (19). Actually, the atomic level widths for the transitions inside the P shell are much less than the widths of the neutron resonances ($\sim 3 \times 10^{-2}$ eV). Therefore, it is nuclear widths which were used for the calculation of the resonance conversion factors R in these cases. The resonance transition characteristics found in this way are listed in Table 2. As it can be seen from the table, values of R, especially for the $M1$ transitions from the K shell and in the P and Q shells, reach very large magnitude and may increase noticeably the probability of the low-energy compound–compound radiative nuclear transitions in the neutron resonances.

Taking into account the RC factor, the probability of a neutron resonance deexcitation via electromagnetic transitions which coincide in the energy with a transition in the atomic shell, is given by the expression

$$W = (1 + R)\frac{\Gamma_i}{\Gamma_0}, \quad (21)$$

where Γ_i is the partial reduced width for the radiative nuclear transition at the resonance energy listed in the third column of Table 2, Γ_0 is the total radiative width. $\Gamma_0 \approx 0.03$ eV for the nuclear range under consideration. Unfortunately, there is practically no information on the spectra of γ quanta with low energies (<100 keV) emitted in the neutron resonance deexcitation. Therefore, we deal with the situation when the Γ_i values are unknown, whereas the (n, $\gamma\alpha$) reaction itself was observed where the α decay was preceded by emission of a low-energy γ quantum with the multipolarity $E1$ or $M1$ [18]. A rough estimation of Γ_i may be obtained by extrapolation to low energies of experimental spectra of radiation emitted in the deexcitation of levels after the thermal neutron capture [18–20] taking into account the ω^3 decrease for the values of Γ_i. Such estimations of Γ_i/Γ_0 are presented in Table 2. As it can be seen from the table, with the assumptions outlined, Γ_i/Γ_0 turns out to be less noticeable than $(1+R)^{-1}$, especially for the low-energy transitions inside the P atomic shell. However, it should be noted that the values of Γ_i obtained are average ones over many resonances with a wide scatter of parameters. There is a possibility of considerable deviations from the average values for specific resonances as well as a manifestation of nonstatistical effects. Consequently, a considerable influence of resonance conversion on the neutron resonance decay and the occurrence of the secondary particle spectra in the decay may not be ruled out.

In the case of higher-energy transitions from the K shell where the uncertainties mentioned above are less, one may expect rather large values of the R factor for the transitions to the Rydberg levels. The levels have a small width ($\ll$1 eV) and a high density. Of great interest is an example with transitions between the atomic levels involving the K and L shells. In this case, the atomic level width (52 eV) is considerably higher than the distance between the neutron resonances, therefore the resonance electron transitions will be universally present. These cases deserve a special consideration.

6. CONCLUSION

We studied interaction of the compound nuclear states, formed in the resonance neutron absorption, via mediation of the electron shell. Specifically, we studied mixing of the compound states with different spins and parities. The latter is to be taken into account when studying effects of P violation in α decay. For this purpose, we calculated spectra of the electromagnetic transitions in deexcitation of the compound nucleus, making an accent on the soft part of the spectra. This part is most important for experimental search for the P-violation effects, but at the same time, it is most difficult one for detecting. It is the resolution of the α detector, ΔE_c, which limits the value of the effects which can be detected. With a usual resolution $\Delta E_c \sim 100$ keV, the mixing arising due to both traditional internal and resonance conversion is $\sim 10^{-4}$, which value is generally at the level of mixing through the P-violating nuclear forces. Resonance conversion is of especial interest in view of the fact that at the nuclear excitation energies in the domain of the neutron resonances, the situation is always "resonance" with respect to interaction with the electron shell. There is always available a nuclear transition whose energy coincides with that of an electron transition. For this reason, such a situation is of great interest for further research.

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РЕАКЦИЯ $(n, \gamma\alpha)$, СОПРОВОЖДАЕМАЯ ВНУТРЕННЕЙ И РЕЗОНАНСНОЙ КОНВЕРСИЕЙ

Ю. П. Гангрский, Ф. Ф. Карпешин, М. Б. Тржасковская

Изучаются спектры γ-переходов, внутренней конверсии и α-переходов в реакциях $(n,\ \gamma)$ и $(n,\ \gamma\alpha)$ на ядре $^{143}_{60}$Nd. Вероятности смешивания близких нейтронных резонансов с разными спинами и четностями, возникающего в результате внутренней и резонансной конверсии, изучаются с точки зрения нарушения P-четности. Представлены доказательства того, что α-распад нейтронного резонанса 4^- с энергией 55 эВ в основное состояние, наблюдаемый ранее, может происходить благодаря такому воздействию внутренней или резонансной конверсии.