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

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We considered spectra of γ, internal conversion and α transitions in (n, γ) and $(n, \gamma\alpha)$ reactions on $^{143}_{60}$Nd. Probabilities of mixing of the close neutron resonances arising due to resonance conversion are also considered. Arguments are presented in favour of that the α decay of the 55-eV neutron resonance 4^- to the ground state, observed in [1], may be due to such a resonance conversion interaction.

1 Introduction

Brilliant effects were detected in the reaction (n, α) [2]. Experiments for the nuclei ^{147}Sm revealed the anomaly large α-width of neutron resonances 4^-, which exceeded the α-width of resonances 3^-. The most intensive α-transitions from the 4^- resonances to the ground nuclear state 0^+ are forbidden in parity, so the result just mentioned may be interpreted as violation of space parity at the level of 100%. On the other hand, in paper [1] and others, the reaction $(n, \gamma\alpha)$ was studied. In these experiments, the gamma-quantum was not detected. Instead, the α-particle energy was determined. In such an approach, a question of low-energy radiative transitions remains open because the resolution of alpha detectors is of the order of tens keV. Broadly speaking, the radiative transition probability is proportional to $\sim \omega^3$. So the most probable transitions are those with an energy of the order of several MeV which may be easy revealed by the α-detector. However, the conversion processes are kept from touching. As is well-known, the internal conversion (IC) probability depends on a transition energy much smoother, so that $M1$ internal conversion coefficients (ICC) remain constant at the threshold [3, 4, 5]. We recall that the $M1$ transitions are important in the case of radiative transitions of small energy between the compound nuclear states [7]. As a result, the probobility of a conversion transition with the energy of several keV may be close to that for a transition with an energy of several tens keV, and even higher than for the transition energies of hundreds keV. This is because the IC probability then fast decreases with the transition energy. Furthermore, below the threshold of the IC, there is onset of discrete, or resonance conversion, which may be even stronger than traditional one [4]. The nuclear energy can be transferred to an atomic electron which is lifted up to a discrete level.

Such a situation might be observed in [1] in reaction of ^{143}Nd(n, α) with resonance neutrons. In the α-particle spectrum, 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 analyse a possibility of the situation. The effect may be due to low-energy transitions between resonances which we will see are strongly facilitated in comparison with radiative transitions by traditional or resonance IC. If the energy of such transitions is smaller than the energy resolution of the α detector, such transitions may appear as direct transitions to the ground state. Note that the resonance electron transitions with the relevant energy

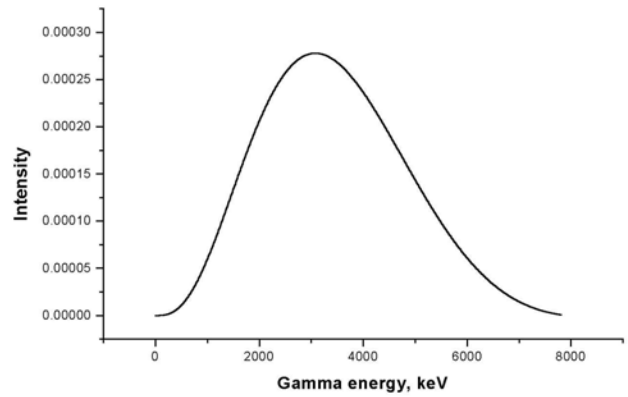

Figure 1: Theoretical gamma-quantum spectrum of transitions from the 55-eV neutron resonance in the nucleus ^{143}Nd.

of around 5 eV may be found practically in any atom [6] either due to a high level density in a nucleus ($\sim$ 200 in the energy interval of 1 keV) in the case of resonance conversion in the valence shell, or due to large widths of atomic levels (to several tens of eV) in the case of the hole in the K atomic shell.

We consider resonance conversion factors along with ICC for transitions down to very low energies of the order of the distance between levels in the P shell of the atom (principal quantum number $n = 6$). It should be noted that Wigner as well as Lyuboshitz et al. [8] pointed out the possibility of interaction of nuclear states via the electron shell. The effect was found experimentally in muonic atoms. In paper [9], mixing of the 3/2+ and 5/2+ levels in the H-like ions of ^{229}Th was predicted.

2 Method of calculation

The energy of a compound-nucleus may be written as

$$E_{\text{ex}} = S_n + E_n \tag{1}$$

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 gamma-rays from the nucleus $^{144}_{60}$Nd, $S_n = 7.81702$ with the excitation energy $E_{\text{ex}} = 7.817075$ MeV (the 55-eV resonance). The probability of the radiative transition was assumed to be proportional to $\sim \omega^3$ as follows:

$$\frac{dP_\gamma}{d\omega} = f\omega^3\rho(E_{\text{ex}} - \omega), \tag{2}$$

where the nuclear level density $\rho(E)$ is written as [10]

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

with the level density constant $a = A/8$ MeV^{-1}, A being the mass number. Respectively, the probability of radiative transition with the energy $\omega_k = E_{\text{ex}} - E_k$ to a specific final

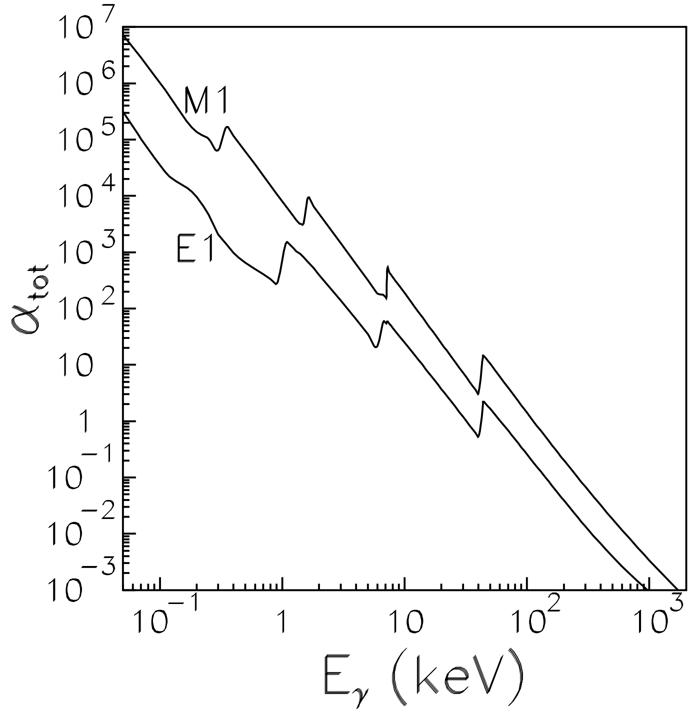

Figure 2: The total ICC values α_{tot} for the $E1$ and $M1$ transitions *versus* the transition energy E_γ for the atom of ^{143}Nd.

state of a nucleus k with the energy E_k has the form

$$P_\gamma^k = f\omega_k^3. \tag{4}$$

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

$$P_\gamma = \int_0^{E_{\rm ex}} \frac{P_\gamma(\omega)}{d\omega} \rho(E_{\rm ex} - \omega)\, d\omega \tag{5}$$

at unity as follows:

$$f = \left[\int_0^{E_{\rm ex}} \omega^3 \rho(E_{\rm ex} - \omega)\, d\omega \right]^{-1} \tag{6}$$

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

As one can see from Fig. 1, maximum of the spectrum is at approximately 3 MeV. The shape of the radiative spectrum in Fig. 1 does not change with the allowance for the IC channel. However, the resulting probability of a soft electromagnetic transition becomes essentially higher due to large values of internal conversion coefficient (ICC), in accordance with what is said in the Introduction. The total ICC values are plotted in Fig. 2. The conversion threshold which is equal to the ionisation potential of the valence shell, begins at about 7 eV for 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 to the values of the order of unity at the energies of about 100 keV. For the IC channel, the expressions should be multiplied by the total ICC $\alpha^{\tau L}(\omega)$, where τL are the type and the multipole order of the transition. As a result of the substitution, if the total probability of the electromagnetic transitions, both radiative and IC transitions is normalised at unity, the constant f (6) goes over the following expression:

$$f_c = \left\{ \int_0^{E_{\rm ex}} [1 + \alpha^{\tau L}(\omega)]\omega^3 \rho(E_{ex} - \omega)\, d\omega \right\}^{-1}. \tag{7}$$

Note that relative probability of the electromagnetic decay for the $M1$ transitions is equal to $6.19 \cdot 10^{-7}$ at energy ≤ 30 keV and $2.43 \cdot 10^{-6}$ at energy ≥ 50 keV. For the $E1$ transitions, the probabilities are $1.14 \cdot 10^{-7}$ and $5.41 \cdot 10^{-7}$, respectively.

3 Reaction $(n, \gamma\alpha)$

Let us define the probability of $(\gamma\alpha)$ decay of a compound nucleus with emission of a gamma quantum with the energy ω and α particle with the energy $E_{\rm ex} - \omega$ as follows:

$$\frac{dP_{\gamma\alpha}(\omega)}{d\omega} = f_\alpha \frac{dP_\gamma(\omega)}{d\omega} P_\alpha(E_{\rm ex} - \omega), \tag{8}$$

where $P_\alpha(E_\alpha)$ is the probability of the α decay of the nucleus with the energy E_α to the ground state, and f_α is the normalisation constant. Let the α decay probability be

$$P_\alpha(E_\alpha) = \exp(-S) \tag{9}$$

with the action

$$S = \int_{r_1}^{r_2} \sqrt{2m_\alpha(V(r) - E_\alpha)}\, dr, \tag{10}$$

where 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. As in (6) and (7), the total probability of the γ, α transitions may be normalised at unity:

$$f_\alpha = \left\{ \int_0^{E_{\rm ex}} [1 + \alpha^{\tau L}(\omega)] \frac{dP_\gamma(\omega)}{d\omega} P_\alpha(E_{\rm ex} - \omega)\, d\omega \right\}^{-1}. \tag{11}$$

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 $\omega_k = E_{\rm ex} - E_k$ may be written as

$$P_{\gamma\alpha}^{(k)} = f_\alpha P_\gamma^{(k)}(\omega_k) P_\alpha(E_{ex} - \omega_k). \tag{12}$$

Furthermore, the probability of the resonance conversion γ, α transition will be

$$P_{c\alpha}^{(k)} = f_\alpha P_c^{(k)} P_\alpha(E_{\rm ex} - \omega_k). \tag{13}$$

In Fig. 3, we present the photon spectrum in the γ, α decay of the compound ${}^{144}_{60}$Nd nucleus, calculated by means of (8), (11). As the tunneling probabilities of the α particle through the barrier strongly increases with its energy, the maximum of the curve in Fig. 3 becomes sharper and shifts considerably towards the softer energies.

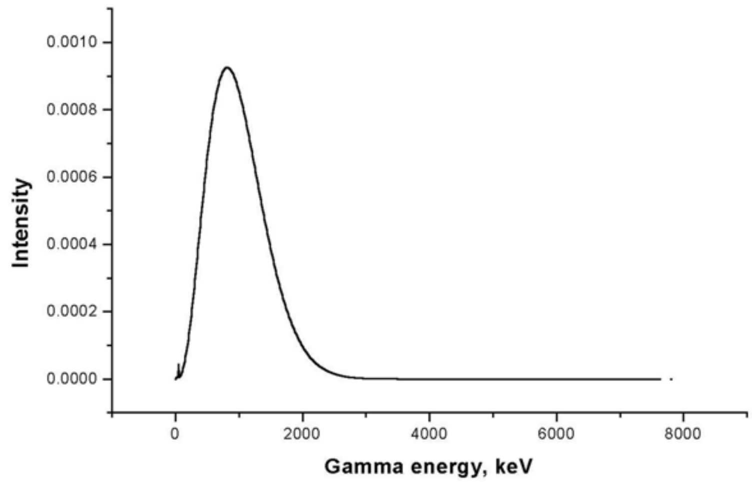

Figure 3: Calculated γ quantum spectrum in the reaction ${}^{143}_{60}$Nd $(n,\gamma\alpha)$ ${}^{140}_{58}$Ce.

4 Calculation of resonance conversion coefficients for low-energy transitions

Theory of the resonance conversion process and the procedure of calculation of relevant coefficients are given in details in [9, 12, 13]. The resonance conversion factor, that is the ratio of widths of the conversion Γ_c and radiative Γ_γ transitions, are given in the vicinity of a resonance by the expression:

$$R = \frac{\Gamma_c}{\Gamma_\gamma} = \frac{\alpha_d \Gamma}{2\pi\left[\Delta^2 + (\Gamma/2)^2\right]} \ , \tag{14}$$

where α_d is the resonance counterpart for conventional ICC, Δ is the resonance defect which is equal to the difference between the atomic and nuclear levels ($\Delta = E_a - E_n$), Γ is the total resonance width including widths of atomic and nuclear levels. The total width is $\sim 10^{-2}$ eV for neutron resonances and depends on an electron shell for the atomic level. For the lowest K shell, Γ reaches several tens of eV but decreases rapidly with increase in the shell principal quantum number n as well as decrease in the radiative transition energy E_n as follows

$$\Gamma \ = \ \frac{E_n^3}{n^3} \tag{15}$$

in accordance with (2). For example, $\Gamma \approx 10^{-8}$ eV for transitions between the ground state of an atom and one of its excited levels with the energy of the order of several eV.

The expression for the resonance conversion factor which is responsible for the contribution of the effect into the radiative transition probability, has the following form in the case of the exact resonance:

$$R \ = \ \frac{2\alpha_d}{\pi\Gamma} \ . \tag{16}$$

For the present purposes of assessing the role of the soft electromagnetic transitions in the $(n, \gamma\alpha)$ reaction on $^{143}_{60}$Nd it is enough to use the resonance conversion coefficients α_d for transitions in the neighbouring nucleus of ^{148}Sm which are calculated in [6]. These transitions are in resonance with electron transitions $1s \rightarrow 6p_{3/2}$ and $6s \rightarrow 6p_{3/2}$ ($E1$ transitions), as well as $1s \rightarrow 7s$ and $6s \rightarrow 7s$ ($M1$ transitions). Note, that conversion $M1$ transitions are the strongest ones just between the s states while radiative transitions between them are strongly prohibited. The lowest levels in the P shell with configurations mentioned above with energies 1.5 eV and 2.8 eV, respectively, were considered. Calculations were performed within the framework of the Dirac–Fock method with regard for finite nuclear size as well as the highest quantum-electrodynamic corrections for vacuum polarisation and the electron self-energy [9]. The atomic level widths were obtained using the well-known value $\Gamma = 52$ eV [14] for the transition between the L_2 and K atomic shells as well as eq. (15). Atomic level widths for the transitions inside the P shell are much less than the widths of the neutron resonances ($3 \cdot 10^{-2}$ eV). Therefore, values of nuclear widths were used for the calculation of the resonance conversion factors R. The resonance transition characteristics found by this way are listed in Table 1. As it can be clearly seen from the table, values of R, especially for the $M1$ transitions from the K shell and inside the P shell, reach very large magnitude and may increase noticeably the probability of the low-energy radiative transitions from neutron resonances.

Table 1: Resonance conversion characteristics for radiative transitions in the nucleus ^{148}Sm with the transition energy E_n

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

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

$$W = (1 + R) \frac{\Gamma_i}{\Gamma_0} , \tag{17}$$

where Γ_i is the partial reduced width for the radiative compound-compound nuclear transition at the resonance energy listed in the third column of Table 1, Γ_0 is the total radiative width of a neutron resonance ($\Gamma_0 \approx 0.03$ eV for the nuclear range under consideration). Unfortunately, there is practically no information on spectra of γ-quanta with low-energies (< 100 keV) emitted at the neutron resonance deexcitation. Because of this, values of Γ_i are unknown as a rule though the reaction $(n,\gamma\alpha)$ was observed where α-decay was preceded by emission of the low-energy γ-quantum with the multipolarity $E1$ or $M1$ [15]. A rough estimation of Γ_i may be obtained by extrapolation to low energies of experimental spectra of γ-radiation emitted at the deexcitation of levels after the heat neutrons capture [15, 16, 17] taking account for values of Γ_i decrease as the third power of the transition energy. Such estimations of Γ_i/Γ_0 are presented in Table 1. As is seen, with the assumptions outlined, Γ_i/Γ_0 turns to be less noticeably than $(1+R)^{-1}$, especially for the low-energy transitions inside the P atomic shell. However it should be noted that values of Γ_i obtained are average over many resonances with a wide scatter of parameters. There is a possibility of appreciable deviations from average values for specific resonances as well as a manifestation of non-statistical effects. Consequently, a prominent influence of resonance conversion on the neutron resonances decay and the occurrence of the secondary particle spectra at the decay must not be ruled out.

In the case of the higher energy transitions from the K shell where the uncertainties mentioned above are less, one may expect rather large values of factor R for 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 atomic levels of the K and L shells. In this case, the level width in the L shell (52 eV) is considerably higher than the distance between neutron resonances so a resonance electron transition will be universally present. However, these cases require a more sophisticated treatment.

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