ЯДЕРНА ФІЗИКА

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A. Ya. Dzyublik

Institute for Nuclear Research, National Academy of Sciences of Ukraine, Kyiv

TRIGGERING OF $^{178}Hf^{m2}$ BY PHOTOINDUCED ELECTRON TRANSITION

We considered the NEET (nuclear excitation by electron transition) as a possible triggering mechanism of the isomer $^{178}Hf^{m2}$ during ionization of the L_3 atomic shell by x-rays. This 16^+ isomer is assumed to be excited into an intermediate state 15^- by E1 electronic transition between M_5 and L_3 shells. Simple nonrelativistic formulas are derived for the NEET probability. The estimations show the probability to be less than the experimental data of [1] by one order of magnitude. The intermediate level is found to decay bypassing the isomeric level 16^+, if the nucleus attributes a triaxial shape in the 15^- state and, besides, there exists a level 13^- shifted with respect to 15^- by 400 keV. We have shown also that the NEET cross section $\sigma_{\mathrm{NEET}}(E)$ as a function of the energy of x-ray photons E, has to accept constant value above the L_3 photoionization threshold in contrast to narrow peak observed by [1].

Keywords: nuclear isomers, NEET, induced nuclear decay, x-rays, hafnium, nuclear spectra.

Introduction

Excited isomeric states of ^{178}Hf for long time attract great attention. Among them the 16^+ 4-quasi-particle level with the energy $W_i = 2446.09$ keV has the longest half-life $T_{1/2} = 31$ yr. In this state spin projection on the symmetry axis $K_i = 16$ much exceeds K_f of lower-lying levels and therefore deexcitation transitions are strongly forbidden. The m2 isomer 16^+ decays by E3 transition into the 13^- level with the energy 2433.334 keV and $K = 8$, which belongs to the rotational band with the band-head 8^- (m1 isomer), located at 1147.41 keV and having the half-life $T_{1/2} = 4$ s.

It would be very attractive to release instantly huge energy stored in the sample with such isomeric nuclei by affecting it with any external fields. Therefore Collins et al. [1 - 6] in a long series of experiments have been trying to trigger the 16^+ isomer by x-rays. They observed slight increase of intensities for some γ-lines as well as appearance of new lines in the deexcitation spectrum of $^{178}Hf^{m2}$, that allowed them to state about 2 % acceleration of the isomer decay. It was suggested that x-ray photons induced transitions into an upper-lying intermediate K-mixing level of hafnium, that cascaded up to the ground state. However, the Collins's results contradict to existing nuclear models (see the review [7]) and alternative experiments with synchrotron radiation [8, 9].

Really, direct absorption of x-ray photons by the m2 isomer is very weak. Therefore it was suggested [2] that the observed effect is provided by the NEET. In this event the x-ray photon ionizes one of the inner atomic shells, then an electron from an upper level fills the hole and simultaneously transfers its energy to the nucleus. The NEET is possible if the nuclear and atomic transitions have the same multipolarity and close-lying energies [10 - 17].

Most refined NEET experiments were conducted on the golden film containing ^{197}Au [15], where the M1 transition from the ground state $3/2^+$ to the first excited one $1/2^+$ was excited by the resonant hole transition. Varying energy of incident x-ray photons they observed the NEET edge, shifted with respect to the K absorption edge higher in energy by 40 eV. The measured NEET probability amounted $P_{NEET} = 4.5 \cdot 10^{-8}$. Similarly, the accelerated decay of $^{178}Hf^{m2}$ was observed [1] when the energy of x-ray photons E exceeded the L_3 photoionization threshold by 6 eV. The corresponding NEET probability was found to be $P_{\mathrm{NEET}} = 1.6 \cdot 10^{-3}$. Such large value might be provided by E1 transitions, which are, in principle, more intensive than M1 transitions.

The probability P_{NEET} of photoinduced NEET for the isomer $^{178}Hf^{m2}$ has been calculated in the framework of the quantum electrodynamics in [16, 17]. It was assumed that the nucleus ^{178}Hf in the intermediate state conserved its axial shape. Then the nucleus practically always returns to the initial isomeric level. As a result, these authors concluded that Collins's team overestimated the effect at least by 15 orders of magnitude.

In present paper we consider the NEET on $^{178}Hf^{m2}$ in the nonrelativistic approach, which allows to avoid cumbersome numerical calculations and get simple formulas. Main attention is paid to the shape of the NEET cross section $\sigma_{NEET}(E)$ versus the energy of the incident x-ray photons E as well as to possible decay path of the intermediate nuclear level around the initial isomeric state 16^+.

NEET cross section

The cross section for photoinduced decay of the isomer through the NEET channel is determined by the product [13, 14]

$$\sigma_{ind} = R\sigma_{NEET}(E), \tag{1}$$

where the branching ratio

$$R = \sum_{f \neq i} \Gamma^n_{ef} / \Gamma^n_e, \tag{2}$$

Γ^n_{ef} are the partial widths for deexcitation transitions from the excited level e into levels f, bypassing the isomeric state, Γ^n_e is the total width of the excited level.

General expression of the NEET cross section at the L_3 absorption edge is given by the integral over the energy of ejected photoelectron $\varepsilon = \hbar^2\kappa^2 / 2m$ [13, 14]:

$$\sigma_{NEET}(E) = E^2_{int}\left(\frac{\Gamma_f}{2\pi}\right)\int_0^\infty \frac{\sigma_{ion}(\varepsilon)d\varepsilon}{[(\varepsilon-\Delta E)^2 + (\Gamma_i/2)^2][(\varepsilon-\Delta E+\delta)^2 + (\Gamma_f/2)^2]}, \tag{3}$$

where

$$\delta = E^n_0 - E^a_0 \tag{4}$$

is the mismatch of the nuclear (E^n_0) and electron (E^a_0) transition energies, $\sigma_{ion}(\varepsilon)$ denotes the ionization cross section of the L_3 level, Γ_i and Γ_f are the widths of the initial and final atomic hole states, $\Delta E = E - B(L_3)$ and $B(L_3)$ is the binding energy of the L_3 electron.

Following [18] it can be shown that the ionization cross section of the L_3 level in the dipole approximation is determined by the expression

$$\sigma_{ion}(\varepsilon) = \left(\frac{\eta}{2}\right)^{10} \frac{0.4 + (\eta/2)^2}{\left[1 + (\eta/2)^2\right]^6} \frac{f(\eta)}{f(\infty)}\sigma_{ion}, \tag{5}$$

where η denotes the Coulomb parameter:

$$\eta = \frac{mZe^2}{\hbar^2\kappa}, \tag{6}$$

the factor $f(\eta)$ denotes the following expression:

$$f(\eta) = \frac{\exp\{-4\eta \cdot arccot(\eta/2)\}}{1 - e^{-2\pi\eta}}, \tag{7}$$

which tends to $f(\infty) = e^{-8}$ as $\eta \to \infty$, and $\sigma_{ion} \equiv \sigma_{ion}(0)$ is the cross section at zero energy of ejected electrons:

$$\sigma_{ion} = \frac{5}{9}2^{18}\pi^2\left(\frac{e^2}{\hbar c}\right)a^2 f(\infty). \tag{8}$$

According to Eqs. (5) - (8) the cross section $\sigma_{ion}(\varepsilon)$ is a slowly varying function of ε and therefore near the NEET edge one can replace $\sigma_{ion}(\varepsilon)$ by the constant $\sigma_{ion} = \sigma_{ion}(0)$. Then integration in Eq. (3) simplifies, giving [14]

$$\sigma_{NEET}(E) = P_{NEET}F_{NEET}(E)\sigma_{ion}, \tag{9}$$

where P_{NEET} stands for the NEET probability [11, 12]:

$$P_{NEET} = \left(1 + \frac{\Gamma_f}{\Gamma_i}\right)\frac{E^2_{int}}{\delta^2 + (\Gamma_i + \Gamma_f)^2/4}. \tag{10}$$

The edge factor $F_{NEET}(E)$ describes energy dependence of the NEET cross section at the NEET edge [14]:

$$F_{NEET}(E) = \frac{1}{(1 + \Gamma_f/\Gamma_i)[\delta^2 + (\Gamma_i - \Gamma_f)^2/4]}\sum_{m=1}^{3} f_m(E) \tag{11}$$

with

$$f_1(E) = \frac{\Gamma_f}{\Gamma_i}\left[\delta^2 - \left(\frac{\Gamma_i}{2}\right)^2 + \left(\frac{\Gamma_f}{2}\right)^2\right] \times \left[\frac{1}{2} + \frac{1}{\pi}\arctan\left(\frac{2\Delta E}{\Gamma_i}\right)\right],$$

$$f_2(E) = \frac{\delta\Gamma_f}{2\pi}\ln\left[\frac{(\Delta E)^2 + (\Gamma_i/2)^2}{(\Delta E - \delta)^2 + (\Gamma_f/2)^2}\right],$$

$$f_3(E) = \left[\delta^2 + \left(\frac{\Gamma_i}{2}\right)^2 - \left(\frac{\Gamma_f}{2}\right)^2\right] \times \left[\frac{1}{2} + \frac{1}{\pi}\arctan\left(\frac{2(\Delta E - \delta)}{\Gamma_f}\right)\right]. \tag{12}$$

General expression for the coupling parameter E^2_{int} has been derived in [11, 12]. If $ka << 1$, where $a = a_0 / Z$ and a_0 is the Bohr radius, $k \approx E^a_0 / \hbar c$ is the wave vector of virtual photons, one can neglect

the retardation corrections to P_{NEET}, which are of the order of 10 % [10]. In such long-wave approximation the formula for E_{int}^2, derived in [12], reduces to

$$E_{int}^2 = \frac{4\pi}{(2L+1)^2}\left(j_i L \frac{1}{2} 0 \,|\, j_f \frac{1}{2}\right)^2 e^2 R_{fi}^2 B(\lambda L; I_i \to I_e), \quad (13)$$

where j_i and j_f are the initial and final angular momenta of the electronic shells containing the holes, whose transition is matched with the isomer excitation into the intermediate level, $(j_1 j_2 m_1 m_2 \,|\, jm)$ is the Clebsh - Gordan coefficient, $B(\lambda L; I_i \to I_e)$ represents the reduced probability of the λL transition from the initial nuclear state to the excited one [19]

$$B(\lambda L; I_i \to I_e) = \frac{1}{2I_i+1}\sum_{\mu M_i M_e} |\langle I_e M_e \,|\, M_\mu(\lambda L) \,|\, I_i M_i\rangle|^2, \quad (14)$$

determined by the electric $(\lambda = E)$ or magnetic $(\lambda = M)$ multipole operator $M_\mu(\lambda L)$ of the nucleus,

$$R_{fi} = \frac{1}{a^{L+1}}\int_0^\infty d\rho \rho^{-L+1} g_f(\rho) g_i(\rho) \quad (15)$$

is the atomic matrix element expressed in terms of the radial wave functions $g_{i(f)}(\rho)$ of electrons, associated with the vacancies i and f. They depend on the dimensionless radial coordinate $\rho = r/a$ and are normalized as follows:

$$\int_0^\infty g^2(\rho)\rho^2 d\rho = 1. \quad (16)$$

The nuclear electric multipole operator $M_\mu(EL)$ is defined by the sum over all protons with spherical coordinates r_i, θ_i, ϕ_i:

$$M_\mu(EL) = e\sum_{i=1}^{Z} r_i^L Y_{L\mu}(\theta_i \phi_i). \quad (17)$$

In order to take into account screening of the nuclear Coulomb field we shall replace the nuclear charge number $Z = 72$ by the effective values $Z_i' = Z - s_i$ and $Z_f' = Z - s_f$, where the screening corrections $s_i = 4.15$ and $s_f = 21.15$ are calculated by the procedure of Slater (see its description in [20]). Then the nonrelativistic radial wave functions for the electrons, which would fill the initial L_3 hole and the final M_5 hole are [18]

$$g_i(\rho) = \left(\frac{Z_i'}{Z}\right)^{5/2} \frac{1}{2\sqrt{6}} \rho e^{-Z_i'\rho/2Z} \quad (18)$$

and

$$g_f(\rho) = \left(\frac{Z_f'}{Z}\right)^{7/2} \frac{4}{81\sqrt{30}} \rho^2 e^{-Z_f'\rho/3Z}. \quad (19)$$

By simple calculation, one finds the NEET strength for the hole transition $L_3 \to M_5$:

$$E_{int}^2 = \frac{8\pi}{9}(0.4)^{10}\left(\frac{e}{a^2}\right)^2 \times$$

$$\times \frac{(Z_i'/Z)^5 (Z_f'/Z)^7}{[0.6(Z_i'/Z) + 0.4(Z_f'/Z)]^8} B(E1; I_i \to I_e). \quad (20)$$

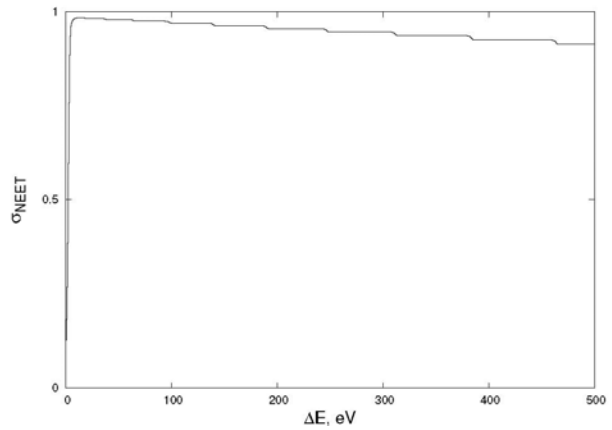
Folowing [16, 17] we put $B(E1) = B_{sp}(E1)$, where the single-particle (Weisskopf) unit for the EL transition is given by [21]

$$B_{sp}(EL) = \frac{e^2}{4\pi}\left(\frac{3}{3+L}\right)^2 R_0^{2L}, \quad (21)$$

and the nuclear radius is $R_0 = 1.2A^{1/3}$ fm.

For the transition $L_3 \to M_5$ in the case of exact resonance $(\delta = 0)$ we obtained the NEET probabilty $P_{NEET} = 2.2 \cdot 10^{-4}$, coinciding with the result of [16]. Other types of E1 transitions appeared to be much less intensive. So, for $L_3 \to M_4$ transition we find $P_{NEET} = 3.8 \cdot 10^{-5}$ compared to $4.4 \cdot 10^{-5}$ of [16] and $2.8 \cdot 10^{-5}$ of [17], and for $L_3 \to M_1$ transition $P_{NEET} = 2.1 \cdot 10^{-6}$, whereas $P_{NEET} = 3.8 \cdot 10^{-6}$ in [16] and $8.0 \cdot 10^{-6}$ in [17].

Center of the NEET edge is located at the energy of incident x-ray photons E^*, for which $F(E^*) = 0.5$. Once $\Gamma_i >> \Gamma_f$, it is shifted with respect to the L_3 absorption edge by $\Delta E^* \approx \delta$ with δ defined in (4). The edge factor $F(E)$ reaches the value ≈ 1 at the distance $\Delta E \approx \delta + \Gamma_s + \Gamma_f$, where Γ_s stands for the width of the energy distribution of the incident x-ray photons [14]. In the case considered the widths are $\Gamma_s \approx 1$ eV [1] as well as $\Gamma_i = 4.55$ eV and $\Gamma_f = 1.52$ eV [22]. Comparing all this with the experimental shift of the NEET peak $\Delta E = 6$ eV [1], we find $\delta = 3.5$ eV. Then the corrected NEET probability at the $M_5 \to L_3$ electron transition becomes $P_{NEET} = 0.9 \cdot 10^{-4}$.



Calculated dependence of the NEET cross section (in units $P_{NEET}\sigma_{ion}$) as a function of $\Delta E = E - B(L_3)$, where E is the energy of incident x-ray photons, counted from the L_3 photoabsorption edge $B(L_3)$.

The edge factor $F_{NEET}(E) = 1$ at all energies of x-ray photons, which satisfy the condition $\Delta E - \delta >> \Gamma_f$ (see also [14]). This means that the accelerated decay of the hafnium isomer had to be observed at all energies above the NEET threshold. On the contrary, the acceleration have been detected [1] only in the narrow interval of the order of 1 eV above the L_3 edge. In order to verify this conclusion we have done exact numerical calculations of the NEET cross section by substituting (9) - (12) into Eq. (3). The results, shown in the Figure, confirm the above statement that the accelerated depletion of the isomer, if it exists, should have been observed at all energies $\Delta E \geq 6$ eV.

Intermediate triaxial shape

Previously it was believed [16, 17] that ^{178}Hf in the hypothetical intermediate state 15^- conserves its prolate axial shape. In this case spin projection on the symmetry axis has definite value $K_e = 15$. As a result, the transitions $15^- \to 13^-$ with alteration of K by $\Delta K = 7$ should be strongly forbidden compared to the backward transition $15^- \to 16^+$ with $\Delta K = 1$. The corresponding extremely small branching ratio $R \sim 10^{-14}$ [19, 20] absolutely annihilates the results of Collins et al. But one can not exclude the situation when the nucleus in the intermediate state attributes a triaxial shape. Then the wave function $|I_e M_e\rangle$ will be spread over the states with different K_e [19]:

$$|I_e M_e\rangle = \sum_{K_e}\sum_{\Omega_e} A^{I_e\tau}_{K_e,\Omega_e}(\gamma)\,|I_e M_e K_e \Omega_e\rangle. \qquad (22)$$

Here the basis components $|I_e M_e K_e \Omega_e\rangle$ are given by

$$|I_e M_e K_e \Omega_e\rangle = \sqrt{\frac{2I_e+1}{16\pi^2}}\left[D^{I_e}_{M_e K_e}(\vartheta)\chi_{\Omega_e}(\mathbf{r}') + (-1)^{I_e} D^{I_e}_{M_e,-K_e}(\vartheta)\chi_{-\Omega_e}(\mathbf{r}')\right], \qquad (23)$$

where $D^{I_e}_{M_e K_e}(\vartheta)$ is the rotation matrix, depending on the Eulerian angles $\vartheta = \{\vartheta_1, \vartheta_2, \vartheta_3\}$, which determine orientation of the coordinate frame ξ, η, ζ bound to the principal axes of the inertia ellipsoid of the nucleus, K_e and Ω_e are the projections of the total (I) and intrinsic (j) angular momenta on the axis ζ, the function $\chi_{\Omega_e}(\mathbf{r}')$ describes intrinsic motion of the nucleons with coordinates r' relative to the axes ξ, η, ζ. The projections take the values $K_e = 1, 3, \ldots 15$ and $\Omega_e = 1, 3, \ldots$.

The expansion coefficients $A^{I_e\tau}_{K_e,\Omega_e}(\gamma)$, depending on the triaxiality parameter γ, satisfy the following orthogonality relations:

$$\sum_{K_e\Omega_e} A^{I_e\tau}_{K_e,\Omega_e}(\gamma) A^{I_e\tau'}_{K_e,\Omega_e}(\gamma) = \delta_{\tau\tau'},$$

$$\sum_{\tau} A^{I_e\tau}_{K_e,\Omega_e}(\gamma) A^{I_e\tau}_{K'_e,\Omega'_e}(\gamma) = \delta_{K_e K'_e}\delta_{\Omega_e\Omega'_e}. \qquad (24)$$

The equations to determine the coefficients $A^{I_e\tau}_{K_e,\Omega_e}(\gamma)$ in odd triaxial nuclei can be found in [19].

Similar K-mixing arises if the nucleus in the 15^- state is γ-soft. Then it may be treated as a rigid triaxial rotator with the effective triaxiality parameter γ_{eff} [19]. Remind that maximum mixing of components with different K_e is achieved when $\gamma_{eff} = \pi/6$. The initial isomeric state 16^+ with the prolate axially-symmetric shape $(\gamma = 0)$ is described by single component $|16, M_i, 16, 16\rangle$.

When we pass to the axes ξ, η, ζ, the electric multipole operator (17) transforms as

$$M_\mu(EL) = \sum_\nu D^L_{\mu\nu}(\vartheta) M'_\nu(EL), \qquad (25)$$

where $M'_\nu(EL)$ depends on the intrinsic coordinates $\mathbf{r}'_i$. By using also the integral

$$\int D^{I_f}_{M_f K_f}(\vartheta)^* D^L_{\mu\nu}(\vartheta) D^{I_e}_{M_e K_e}(\vartheta) d\Omega =$$

$$= \frac{8\pi^2}{2I_f+1}(I_e L M_e \mu\,|\,I_f M_f)(I_e L K_e \nu\,|\,I_f K_f), \qquad (26)$$

one finds the reduced probability for the EL transition per unit time from the excited state $I_e = 15^-$ to any final axially-symmetric state $|I_f M_f K_f, \Omega_f\rangle$ with $\Omega_f = K_f$:

$$B(EL; I_e \to I_f) = \left| \sum_{\nu} \sum_{K_e, \Omega_e} A^{I_e}_{K_e, \Omega_e}(\gamma) (I_e L K_e \nu | I_f K_f) \langle \chi'_{K_f} | M'_{\nu}(EL) | \chi_{\Omega_e} \rangle \right|^2 . \quad (27)$$

Every intrinsic wave function $\chi_{\Omega}(\mathbf{r}')$ can be expanded in the functions $|j\Omega\rangle$, characterized by definite angular momenta j (see, e.g., [23]):

$$\chi_{\Omega}(r') = \sum_j a_j |j\Omega\rangle. \quad (28)$$

Then

$$\langle \chi'_{\Omega_f} | M'_{\nu}(EL) | \chi_{\Omega_e} \rangle =$$

$$= \sum_{j_f j_e} a^*_{j_f} a_{j_e} (j_e L \Omega_e \nu | j_f \Omega_f) \langle j_f \| M'(EL) \| j_e \rangle |^2, \quad (29)$$

where $\Omega_f = K_f$ and $\langle j_f \| M'(EL) \| j_e \rangle$ denotes the reduced matrix element. From Eqs. (27) and (29) it follows that $K_f = K_e + \nu$ and $K_f = \Omega_e + \nu$. That is only components with $K_e = \Omega_e$ of the 15^- wave function are involved in the electromagnetic transition.

For estimation of $B(EL)$ we shall demand that for every transition

$$|\langle \chi'_{\Omega_f} | M'_{\nu}(EL) | \chi_{\Omega_e} \rangle|^2 = B_{sp}(EL). \quad (30)$$

Then in correspondence with (27) for the E1 transition from 15^- to 16^+ one has

$$B(E1; 15^- \to 16^+) = \left(A^{15}_{15,15}(\gamma) \right)^2 B_{sp}(E1), \quad (31)$$

while for the E2 transition from $I_e = 15^-$ to $I_f = 13^-$ with the energy 2433.334 keV and spin projection $K_f = 8$

$$B(E2; 15^- \to 13^-) \sim$$

$$\sim \left| \sum_{K_e, \nu} A^{15}_{K_e, K_e}(\gamma) (15, 2, K_e \nu | 13, 8) \right|^2 B_{sp}(E2), \quad (32)$$

where $K_e = 6, 8, 10$.

The unit-time probability for the EL transition is related to the reduced probability by [19]

$$P(EL; i \to f) = \frac{8\pi(L+1)}{\hbar L[(2L+1)!!]^2} k^{2L+1} B(EL; i \to f), \quad (33)$$

where k is the wave vector of emitted γ-quanta.

Substituting (31), (32) into (33) and adopting that all the expansion coefficients $A^{15}_{K_e, K_e}(\gamma)$ are approximately equal, we arrive at the branching ratio

$$R = \frac{P(E2; 15^- \to 13^-)}{P(E1; 15^- \to 16^+)} \sim 10^{-7}, \quad (34)$$

but not $R \sim 10^{-14}$ as predicted in [16, 17].

Discussion

The hafnium atomic binding energies are $B(L_3) = 9560.7 \pm 0.4$ eV and $B(M_5) = 2600.9 \pm \pm 0.4$ eV [24], so that the electron transition energy $E^a_0 = 6.9598$ keV. The energy of the nuclear transition, involved in NEET, differs from E^a_0 only by few eV [1]. Therefore the intermediate level 15^- should have the energy $W_e = 2453.05$ keV.

Note that our nonrelativistic calculations of the probability P_{NEET} for excitation of the intermediate 15^- level via the atomic electrons astonishingly well correlate with more cumbersome exact relativistic Hartri - Fock calculations [16, 17]. Therefore analyzing NEET in other nuclei one can apply analogous simple estimations. Above the L_3 absorption edge we calculated the NEET probability $P_{NEET} = 0.9 \cdot 10^{-4}$, being by one order less than the experimental result $P_{NEET} \cdot R = 1.6 \cdot 10^{-3}$ [1].

Up to now the main theoretical argument [16, 17] against validity of the experimental results [1] was very low branching ratio R for deexcitation transition of the 15^- level into 13^- level against the transition, which returns the nucleus back in the 16^+ isomeric state.

An assumption of the nuclear shape triaxiality in the intermediate 15^- state allows us to increase previous estimations of R by 7 orders. However, this estimation (34) again shows that the deexcitation path $15^- \to 13^-$ is too weak to be possible. The main reason of such weakness is that the 13^- level is separated only by 19.72 keV from the 15^- level. The situation is improved if there is one more $13^-_?$ level, which is located much lower.

Let the energy of transition $15^- \to 13^-_?$ be 400 keV. Then we already get $R \sim 1$. Note, however, that the expansion amplitude $A^{15}_{15,15}$ is greater than all other amplitudes $A^{15}_{K_e,\Omega_e}$ with $K_e, \Omega_e < 15$, and hence the real value of R may be somewhat lower. Of course, more fundamental theory of electromagnetic transitions in the triaxial nuclei is needed, similar to that, given in [28] for odd nuclei, treated as an even-even core + one nucleon.

The m2 isomer spontaneously decays to the 13^- level with the spin projection $K = 8$ but not in any hypothetical $f = 13^-_?$ level. Therefore we ought to assume also that the corresponding spin projection $K_f < 8$. This is possible if the $13^-_?$ level belongs to any yet unknown rotational band with $K_f < 8$. Then the decay of the intermediate level 15^- will proceed around the rotational band, built on the m1 isomer. Such our conclusion correlates, in principle, with observations of [1]. They detected an induced prompt decay of the isomer around the 13^- level. On the contrary, the decay via the 13^- level (member of the rotational band of the m1 isomer) would lead to 4 s delay of the emission of γ quanta in final chain of transitions within the ground state band.

Thus, if the nucleus ^{178}Hf has a triaxial shape in the intermediate state 15^-, it can successfully decay in the $13^-_?$ level of still unknown rotational band. However, even in such favorite case our upper estimation of the effect remains less than the experimental data by one order. Possible collectivity of the 15^- level would increase the NEET probability.

The edge factor $F_{NEET}(E) = 1$ at all energies of x-ray photons, which satisfy the condition $\Delta E - \delta >> \Gamma_f$ (see also [17]). This means that the accelerated decay of the hafnium isomer had to be observed at all energies above the NEET threshold. In addition we have done exact numerical calculations of the NEET cross section by substituting (9) - (12) into Eq. (3). The results, shown in the figure, confirm the above statement that the accelerated depletion of the isomer, if it exists, should have been observed at all energies $\Delta E \geq 6$ eV.

At the same time, the decay enhancement vs E in the experiment [1] has been described by very sharp peak, having the width of the order of 1 eV. Perhaps, such a peak is provided by EXAFS oscillations of the ionization cross section above the L_3 absorption edge, which are caused by interference of the emitted photoelectron wave and coherent electron waves backscattered by the neighboring atoms (analysis of this possibility is under way). Note that oscillations of NEET cross section on ^{197}Au, due to the EXAFS effect, have been already observed in [15].

Thus, we see that categorical objections, advanced in papers [16, 17] against findings of [1 - 6], may be removed and therefore the problem of the ^{178}Hf^{m2} enduced depletion remains open.

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О. Я. Дзюблик

ТРИГЕРУВАННЯ $^{178}Hf^{m2}$ ПРИ ФОТОІНДУКОВАНОМУ ЕЛЕКТРОННОМУ ПЕРЕХОДІ

Розглянуто NEET (збудження ядер при електронних переходах) як можливий механізм тригерування ізомеру $^{178}Hf^{m2}$ при іонізації атомної оболонки L_3 рентгенівськими променями. Вважається, що цей ізомер 16^+ збуджується в проміжний стан 15^- при електронному E1-переході між оболонками M_5 та L_3. Виведено прості нерелятивістські формули для ймовірності NEET. Оцінки показують, що ця ймовірність виявляється на порядок меншою від експериментальних даних [1]. Знайдено, що проміжний стан 15^- розпадається в обхід ізомерного рівня 16^+, якщо ядро в стані 15^- має неаксіальну форму і, крім того, існує ще рівень 13^-, зміщенний на 400 кеВ відносно 15^-. Показано також, що переріз NEET $\sigma_{\mathrm{NEET}}(E)$, як функція енергії рентгенівських фотонів E, досягає постійного значення вище порога іонізації L_3-оболонки на відміну від вузького піка, що спостерігався в [1].

Ключові слова: ядерні ізомери, NEET, індукований розпад, рентгенівські промені, гафній, ядерні спектри.

А. Я. Дзюблик

ТРИГГЕРОВАНИЕ $^{178}Hf^{m2}$ ПРИ ФОТОИНДУЦИРОВАННОМ ЭЛЕКТРОННОМ ПЕРЕХОДЕ

Рассмотрено NEET (возбуждение ядер при электронных переходах) как возможный механизм триггерования изомера $^{178}Hf^{m2}$ при ионизации атомной оболочки L_3 рентгеновскими лучами. Предполагается, что этот изомер 16^+ возбуждается в промежуточное состояние 15^- при электронном E1-переходе между оболочками M_5 и L_3. Выведены простые нерелятивисткие формулы для вероятности NEET. Оценки показывают, что эта вероятность оказывается на порядок меньшей экспериментальных данных [1]. Найдено, что промежуточный уровень 15^- распадается в обход изомерного уровня 16^+, если ядро в состоянии 15^- имеет неаксиальную форму и, кроме того, существует еще уровень 13^-, смещенный на 400 кэВ относительно 15^-. Показано также, что сечение NEET $\sigma_{\mathrm{NEET}}(E)$, как функция энергии рентгеновских фотонов E, приобретает постоянное значение выше порога ионизации L_3-оболочки в отличие от узкого пика, наблюдавшегося в [1].

Ключевые слова: ядерные изомеры, NEET, индуцированный распад, рентгеновские лучи, гафний, ядерные спектры.

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