Processes of the nuclear isomer ^{229m}Th(3/2$^+$, 3.5 ± 1.0 eV) resonant excitation by optical photons

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Processes of the Nuclear Isomer ^{229m}Th(3/2$^+$, 3.5 ± 1.0 eV) Resonant Excitation by Optical Photons

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Abstract

The excitation processes of the low energy isomeric level in nucleus ^{229}Th by optical photons are investigated for different values of relations between energies of nuclear transition and photons. The role of the atomic shell, which "works" as electron bridge, is considered. The cross-sections of the resonance nuclear excitation by laser beam (the narrow line) and by special lamp (the wide line) are calculated. The possibilities of experimental researches are discussed.

1. Introduction

The anomaly low energy isomeric level 3/2$^+$, 3.5 ± 1.0 eV exists in the nucleus ^{229}Th. It was discovered in [1, 2] after the detailed experimental investigation of the level scheme of ^{229}Th. The existence of such a level opens a unique possibility for investigation of some very interesting and important physical problems. The main of them are the following: a process of nuclear isomer excitation by a laser beam; a decay of nuclear isomeric level via electronic bridge; the investigation of the chemical environment and electronic properties of solids by means of measuring the half-life time of isomeric levels and energies of emitted photons; development of a high stability nuclear source of light for metrology; creation of γ-laser in the optical range, and so on.

Let us consider, for example, the investigation of chemical environment. It is well known that isomer ^{235m}U(1/2$^+$, 76.8 eV) is widely used for researching external atomic shells hybridization and surface properties by means of introduction of uranium atoms into various media [3]. However, the useage of isomer ^{229m}Th(3/2$^+$, 3.5 eV) has evident advantages: registration of optical photons instead of very low energy electrons and, as a consequence, a possibility of measuring the spectrum of emitted photons; higher sensitivity for chemical environment of valence electron $6d_{3/2}$- and $7s_{1/2}$-subshells, which play a main role in the decay of ^{229m}Th via electron bridge in a thorium atom (in comparison with uranium, where conversion takes place mainly at filled electron $6p_{1/2,3/2}$-subshells, and valence electron subshells $5f_{5/2}$, $6d_{3/2}$, $7s_{1/2}$, which are very sensitive to the chemical environment, take a very small role at the conversion decay of ^{235m}U). That is, thorium atoms with nuclei ^{229m}Th could be used as a super-sensitive probe for investigation of properties of materials.

A large amount of ^{229m}Th isomers is necessary for the experimental research of the processes mentioned above. But an isomeric state is rarely populated at ^{233}U α-decay [4]. That is why the simple and high effective method of isomer excitation should be developed and used. Taking into account that $E_{\text{i.s.}}$ lies in the optical range, lasers or specials lamps may be used for this purpose. The process of ^{229m}Th excitation via atomic shell by a laser beam was suggested for the first time in [5] for the special case of non-resonant nuclear excitation. Here we consider all possible processes of ^{229m}Th resonant excitation by optical photons including cases of narrow and wide lines. Adopted system of units is $\hbar = c = 1$.

2. Photoexcitation of the nuclear isomer

The simplest process of nuclear excitation is a first-order process of direct photo excitation by photons whose energies ω coincide with the nuclear isomeric transition energy ω_N up to the line width $\Delta\omega$. In this case the resonance cross-section can be evaluated by the formula

$$\sigma_{\text{res}}^{(1)} \simeq \frac{\lambda_N^2}{2\pi} \frac{\Gamma_N^{\text{rad}}(\omega_N;\ \text{g.s.} \to \text{i.s.})}{\Delta\omega_L},$$

where $\lambda_N = 2\pi/\omega_N$ (here $\omega_N = E_{\text{i.s.}}$) and $\Gamma_N^{\text{rad}}(\omega_N;\ \text{g.s.} \to \text{i.s.})$ is the width of the radiative nuclear transition from the ground state (g.s.) to the isomeric one (i.s.). If the reduced probability $B(\text{M1};\ \text{g.s.} \to \text{i.s.})$ approximately equals 10^{-2} Weiskopf units (M1-transition forbidden by asymptotic quantum numbers (see Fig. 1) of Nilsson model), we have $\Gamma_N^{\text{rad}}(\omega_N;\ \text{g.s.} \to \text{i.s.}) \simeq 10^{-20}$ eV in the range $\omega_N = 3.5 \pm 1.0$ eV. The cross-sections are $\sigma_{\text{res}}^{(1)} \simeq 10^{-25}$ cm^2 for a typical laser beam with the ratio $\Delta\omega_L/\omega_L \simeq 10^{-6}$ (the narrow line) in the range $\omega_L \approx \omega_N$, and $\sigma_{\text{res}}^{(1)} \simeq 10^{-30}$ cm^2 for the "lamp" beam with the ratio $\Delta\omega_l/\omega_l \simeq 1$ (the wide line) in the same range $\omega_l \approx \omega_N$.

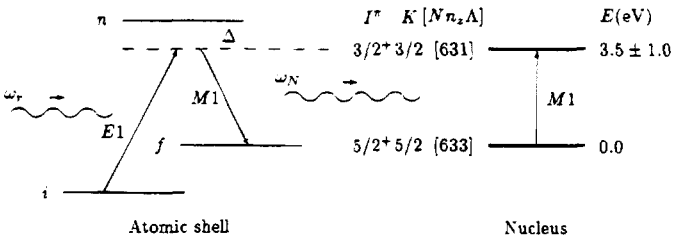

Fig. 1. Scheme of nuclear level resonance excitation at the IEB process.

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The cross-section of the first-order process $\sigma^{(1)}$ becomes large only near the resonance. That is why, it will be very difficult to find the nuclear level by the method of direct photo excitation using a laser beam. It would take some years for passing the energy interval of 2 eV by a laser beam with $\Delta\omega_L \approx 10^{-6}$ eV, because we have to irradiate the target $\simeq 100$ s at each step as it follows from the previous estimations [5].

On the other hand, irradiation of the target by a special lamp with a wide spectrum $\omega_l \pm \Delta\omega_l \approx 3.5 \pm 1.0$ eV provides resonant excitation of nuclei. The cross-section is considerably smaller in this case. But it may be compensated partly by the power of the lamp. In Section 4 we make numerical calculations and show that a special lamp may be used in the first experiments for finding the isomeric level.

3. Nuclear isomer excitation via the inverse electronic bridge

In this section we consider the method of ^{229m}Th excitation via the third-order process of "inverse electronic bridge" (IEB). This method was suggested in [5] for the process of nonresonant nuclear excitation by optical photons via an atomic shell. Here we consider the more important case of resonant nuclear excitation via the IEB.

Two Feynmann diagrams are shown in Fig. 2. They describe an inverse electronic bridge process. The element of the S-matrix, corresponding to the sum of the diagrams, after integration over the time has the form [5]

$$S_{fi}^{(3)} = \sum_n \frac{1}{\mathscr{E}_f + \omega_N - \mathscr{E}_i - \omega + i(\Gamma_i + \Gamma_n + \Gamma_f + \Gamma_{i.s.}^{tot})/2} \times \left\{ \frac{\int d^3r j_{in}^{\rho}(r)\mathscr{A}_{\rho}(r,\omega) \iint d^3r\, d^3R j_{nf}^{\mu}(r) \times D_{\mu\nu}(\omega_N; r-R) J_{g.s.\to i.s.}^{\nu}(R)}{(\mathscr{E}_n - \mathscr{E}_i) - \omega + i(\Gamma_i + \Gamma_n)/2} + \frac{\iint d^3r\, d^3R j_{in}^{\mu}(r) D_{\mu\nu}(\omega_N; r-R) \times J_{g.s.\to i.s.}^{\nu}(R) \int d^3r j_{nf}^{\rho}(r)\mathscr{A}_{\rho}(r,\omega)}{(\mathscr{E}_n - \mathscr{E}_i) + \omega_N + i(\Gamma_i + \Gamma_n + \Gamma_{i.s.}^{tot})/2} \right\}. \quad (1)$$

Here we have used the following notations: $j_{if}^{\mu}(r)$ and $J_{g.s.\to i.s.}^{\nu}(R)$ are the electronic and nuclear currents, which are defined by equations

$$j_{if}^{\mu}(r) = -e\bar{\psi}_f(r)\gamma^{\mu}\psi_i(r),$$

$$J_{g.s.\to i.s.}^{\nu}(R) = e\Psi_{i.s.+}(R)\hat{J}^{\nu}\Psi_{g.s.}(R),$$

where e is the proton charge, $\psi(r)$ is the electronic wave function, and $\Psi(R)$ is the nuclear one, γ^{μ} are the Dirac matrices, $\hat{J}^{\nu}$ is an operator of the electromagnetic nuclear current, $D_{\mu\nu}(\omega_N; r-R)$ is a photon propagator in the coordinate-frequency representation, $\mathscr{A}_{\mu}$ is the photon wave function, $\Gamma_{i,n,f}$ are widths of the atomic initial (i), intermediate (n) and final (f) states (below we put $\Gamma_i = 0$), $\mathscr{E}_{i,n,f}$ are energies of electronic states at atomic shells ($\mathscr{E}_{i,f,n} < 0$). Only binding intermediate states were included in the electron propagator in eq. (1), because the ionization potential I_0 of thorium atom is higher ($I_0 = 6.08$ eV) then $E_{i.s.}$, and hence it would be necessary to use photons with $\omega < I_0$ for excitation.

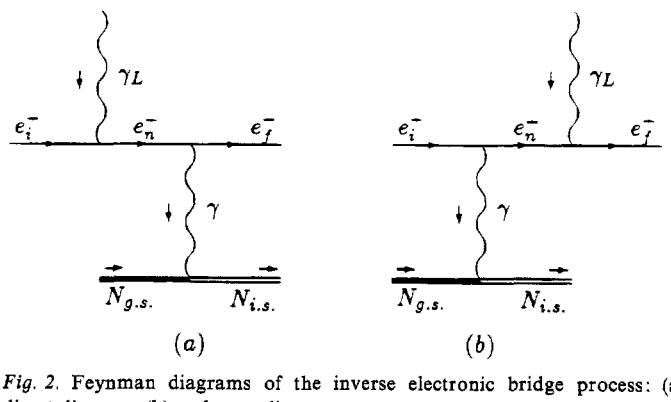

Fig. 2. Feynman diagrams of the inverse electronic bridge process: (a) direct diagram, (b) exchange diagram.

In all cases, which are interesting for us, a main contribution to the cross-section gives a direct diagram in Fig. 2(a). This statement is evident near the resonance, where the energetic denominator in the first term in curly brackets in the eq. (1) becomes small. But a contribution of the exchange diagram is small far from resonance too. It is a consequence of a wave function structure of the electronic (atomic) states connected by E1- and M1-transitions at Fig. 1 and Fig. 2. As it was determined in [5, 6], the values of the corresponding atomic matrix elements are essentially larger for the direct diagram than for the exchange one. It permits us to neglect the contribution of the exchange diagram to the cross-section estimation.

3.1. *Nonresonant excitation of nuclear level*

The following expression is obtained for the cross-section of the IEB process in the single-level approximation if one neglects the contribution of the exchange diagram:

$$\sigma^{(3)}(\omega) \simeq \frac{\lambda^2}{8\pi} \frac{\Gamma_A^{rad}(\omega; i\to n)(\Gamma_n + \Gamma_f + \Gamma_{i.s.}^{tot})}{(\mathscr{E}_n - \mathscr{E}_i - \omega)^2 + (\Gamma_n/2)^2} \times \frac{E_{int}^2(M1; \omega_{n,f}; n\to f; g.s.\to i.s.)}{(\omega + \mathscr{E}_i - \mathscr{E}_f - \omega_N)^2 + (\Gamma_n + \Gamma_f + \Gamma_{i.s.}^{tot})^2/4}, \quad (2)$$

where $\Gamma_A^{rad}(\omega; i\to n)$ is the width of the atomic radiative transition from the initial to the intermediate state, $\omega_{nf} = \mathscr{E}_n - \mathscr{E}_f$, E_{int}^2 is the average value over the initial states, and sum over the final states, of the square of the modulus of the magnetic-dipole interaction energy H_{int} of the electron $j_{nf}^{\mu}(r)$ and nuclear $J_{g.s.\to i.s.}^{\nu}(R)$ currents in the second order of perturbation theory:

$$H_{int} = \iint d^3r\, d^3R j_{nf}^{\mu}(r) D_{\mu\nu}(\omega_{nf}; r-R) J_{g.s.\to i.s.}^{\nu}(R).$$

The very small energy H_{int} induces nuclear excitation at the atomic electron transition (so called NEET process). Theory of the NEET was developed in [7]. The discrepancy between the atomic transition energy ω_{nf} and the nuclear one ω_N leads to the nonresonant nuclear level excitation. Below we will denote this discrepancy as Δ.

Let us consider the more general case of laser irradiation. It is well known, that the δ-function is the limit of a Cauchy delta-like sequence

$$\delta(x) = \lim_{\varepsilon\to+0} \frac{1}{\pi} \frac{\varepsilon}{x^2 + \varepsilon^2}.$$

Therefore we can replace in eq. (2) the function

$$\frac{1}{\pi} \frac{\Gamma_n/2}{(\mathscr{E}_n - \mathscr{E}_i - \omega)^2 + (\Gamma_n/2)^2}$$

by the energy delta-function $\delta(\mathscr{E}_n - \mathscr{E}_i - \omega)$ at the limit $\Gamma_n \to 0$.

Now, integration $\int d\omega g(\omega - \omega_L)\sigma(\omega)$ of the cross-section $\sigma^{(3)}$ over the real shape of the laser line

$$g(\omega - \omega_L) = \frac{1}{\pi} \frac{\Delta\omega_L/2}{(\omega - \omega_L)^2 + (\Delta\omega_L/2)^2}$$

(i.e., by Lorentz one in our case) leads to the simple form for the nonresonant nuclear excitation cross-section via the inverse electronic bridge process ($\sigma^{(3)}_{nres}$) under the resonance tuning of laser radiation at atomic transition from the initial state to the excited intermediate one [5]

$$\sigma^{(3)}_{nres} \simeq \frac{\lambda_{in}^2}{2\pi} \frac{\Gamma_A^{rad}(\omega_{in}; i \to n)}{\Delta\omega_L} P_{NEET}, \tag{3}$$

where $\lambda_{in}(=2\pi/\omega_{in})$ is the wavelength for the atomic transition from the ground state i to the excited intermediate state n, and

$$P_{NEET} = \left(1 + \frac{\Gamma_f + \Gamma^{tot}_{i.s.}}{\Gamma_n}\right) \frac{E^2_{int}(M1; \omega_{nf}; n \to f; g.s. \to i.s.)}{(\mathscr{E}_f - \mathscr{E}_n - \omega_N)^2(\Gamma_n + \Gamma_f + \Gamma^{tot}_{i.s.})^2/4}$$
$$\simeq \frac{E^2_{int}(M1; \omega_{nf}; n \to f; g.s. \to i.s.)}{\Delta^2 + (\Gamma_n/2)^2} \tag{4}$$

is the relative probability of nuclear excitation per one atomic electron transition from the intermediate state to the final state f. We neglect Γ_f and $\Gamma^{tot}_{i.s.}$ is the denominator of eq. (4). $\Gamma^{tot}_{i.s.}$ is very small because the half-life time of the isomeric level probably exceeds 10 s (see Section 3). Γ_f is considerably smaller than Γ_n because, first, the intermediate level n is bound by the E1-transition with the ground state, and second, the excited atomic level f lies approximately 3.5 eV (which is a very big distance for the optical range) lower than the level n. Detailed formulas for calculation of E_{int} and P_{NEET} are represented in [7]. The typical values of E^2_{int} are 10^{-10}–10^{-11} eV^2 [5] for M1-transitions with energies $\omega_{nf} \approx$ 3–4 eV in thorium atom Th^{I} or ions Th^{II-IV}.

3.2. *Resonant excitation of nuclear level*

The scheme of resonant excitation of nuclear level at the IEB process is shown in Fig. 1. The wavelength of the laser radiation is now chosen from the energy conservation condition for the diagrams in Fig. 2. Using the analogy with the previous case we substitute in eq. (2) the function

$$\frac{1}{\pi} \frac{(\Gamma_i + \Gamma_n + \Gamma_f + \Gamma^{tot}_{i.s.})/2}{(\omega + \mathscr{E}_i - \mathscr{E}_f - \omega_N)^2(\Gamma_i + \Gamma_n + \Gamma_f + \Gamma^{tot}_{i.s.})^2/4}$$

by the energy δ-function $\delta(\omega + \mathscr{E}_i - \mathscr{E}_f - \omega_N)$ (which is correct in the limits $\Gamma_{i,n,f} \to 0$ and $\Gamma^{tot}_{i.s.} \to 0$).

Now the integration $\sigma^{(3)}$ over the real shape of the laser line leads to the following form for the resonant nuclear excitation cross-section at the IEB process

$$\sigma^{(3)} \simeq \frac{\lambda_r^2}{4} \Gamma_A^{rad}(\omega_r; i \to n) \frac{1}{\pi} \frac{\Delta\omega_L/2}{(\omega_r - \omega_L)^2 + (\Delta\omega_L/2)^2}$$
$$\times \frac{E^2_{int}(M1; \omega_N; n \to f; g.s. \to i.s.)}{(\mathscr{E}_n - \mathscr{E}_f - \omega_N)^2 + (\Gamma_n + \Gamma_f + \Gamma^{tot}_{i.s.})^2/4}, \tag{5}$$

where $\omega_r = \mathscr{E}_f + \omega_N - \mathscr{E}_i$ is the energy of resonant photons (see Fig. 1). The formula eq. (5) under the condition $\omega_L - \omega_r \leqslant \Delta\omega_L$ (meaning tuning of the laser to the resonant energy ω_r) may be written in the form

$$\sigma^{(3)}_{res} \simeq \frac{\lambda_r^2}{2\pi} \frac{\Gamma_A^{rad}(\omega_r; i \to n)}{\Delta\omega_L} P_{NEET}. \tag{6}$$

This cross-section practically coincides with the nonresonant cross-section eq. (3), because the difference between the wavelengths λ_r and λ_{in} is relatively small, and $E_{int}(\omega_N) \approx E_{int}(\omega_{nf})$. Typical values of the cross-section are $\sigma^{(3)}_{res} \simeq 10^{-21}$–$10^{-22}$ cm^2. Taking into account the large density of excited atomic levels in thorium [8] we could prescribe the value 0.1 eV to the typical discrepancy Δ between ω_N and ω_{nf}.

The number of excited levels in a thorium atom is large as we have said. It means that the situation shown in Fig. 1, may be achieved experimentally more easily, than a direct nuclear photo excitation, by tuning the laser.

On the other hand, the resonant condition exists already for part of the lamp photons. It is evident, because the lamp spectrum $\omega_l \pm \Delta\omega_l/2$ covers the range $\omega_N = 3.5 \pm 1.0$ eV. That is why, the resonant cross-section formulae coincides in this case with eq. (6), where $\Delta\omega_L$ should be substituted by $\Delta\omega_l$.

3.3. *Resonant excitation of nuclear level by nonresonant photons*

Atomic levels and laser lines have widths, which are not equal to zero. Resonant excitation of a nuclear level by nonresonant photons is possible in this case. Let us calculate the cross-section of such a process if the laser radiation is tuned at the wavelength of an atomic transition λ_{in} from the ground state i to the excited intermediate state n as in Section 3.1. For this purpose in eq. (5) we make the necessary "fine-tuning", i.e., put $\omega_L = \mathscr{E}_n - \mathscr{E}_i$. After that we get immediately $\omega_r - \omega_L = \mathscr{E}_n - \mathscr{E}_f - \omega_N = \Delta$ in the denominator of eq. (5). Now the cross-section of the resonant excitation of the nucleus at a fine-tuning for the i → n atomic transition

$$\sigma^{(3)} \simeq \frac{\lambda_r^2}{4} \Gamma_A^{rad}(\omega_r; i \to n) \frac{1}{\pi} \frac{\Delta\omega_L/2}{\Delta^2 + (\Delta\omega_L/2)^2}$$
$$\times \frac{E^2_{int}(M1; \omega_N; n \to f; g.s. \to i.s.)}{\Delta^2 + (\Gamma_n/2)^2} \tag{7}$$

can be reduced to two different cases.

First, when $\Delta\omega_L \geqslant \Delta$. Then

$$\sigma^{(3)} \simeq \frac{\lambda_r^2}{2\pi} \frac{\Gamma_A^{rad}(\omega_r; i \to n)}{\Delta\omega_L} P_{NEET}. \tag{8}$$

Thus the cross-section coincides with the version of the resonant excitation of the nucleus considered above [see eq. (6)].

The second case, which is more probable than the first one realizes, when $\Delta\omega_L \ll \Delta$. Then in the cross-section

$$\sigma^{(3)} \simeq \frac{\lambda_r^2}{8\pi} \frac{\Gamma_A^{rad}(\omega_r; i \to n)}{\Delta\omega_L} \left(\frac{\Delta\omega_L}{\Delta}\right)^2 P_{NEET} \tag{9}$$

one gets a natural additional multiplier of order $(\Delta\omega_L/\Delta)^2$. This result reflects the fact that in the third order of perturbation theory, provided the presence of widths, the process under consideration takes place. But its cross-section is comparatively small and depends on relation between a

laser line width and Δ. In this case Δ coincides with the difference between the laser photon energy ω_L, which is equal to ω_{in}, and the resonance energy ω_r.

Our scheme of searching the level consists in founding at the beginning of the small number of resonance excited nuclei of Th-229 at the fine-tuning for one of atomic transitions. Then it is necessary to remove the laser wave length from that of the atomic transition and fine-tuning of the laser for the resonance excitation of nuclei through the system of atomic levels (see Fig. 1).

The following fact is more important. In this scheme we can reach a nuclear excitation tuning consequently a laser beam at the well known wavelengths of atomic transitions. It differs principally from the attempts to tune a laser at the unknown wavelength of the nuclear transition.

3.4. *Excitation of nuclear level under the double resonance condition*

The value $E_{i.s.}$ is known rather roughly now. Hence we do not know if ω_N coincides with the energy of one atomic M1-transition or not. However, first, the density of excited states is high in a thorium atom [8]. Second, there exist a lot of thorium chemical combines. That is why the coincidences of the energy of the second atomic transition ω_{nf} and ω_N with an accuracy $(\Gamma_n + \Gamma_f + \Gamma^{tot}_{i.s.})$ are possible in principle. The cross-section $\sigma^{(3)}_{dres}$ of IEB in this case of a double resonance (really, here we put $\omega_L = \omega_{in}$ and $\omega_{nf} = \omega_N$) is obtained easily from eqs (3) and (4) under the condition $(\mathscr{E}_n - \mathscr{E}_f) - \omega_N = 0$:

$$\sigma^{(3)}_{dres} \simeq \frac{\lambda^2_{in}}{2\pi} \frac{\Gamma^{rad}_A(\omega_{in}; i \to n)}{\Delta\omega_L} \times \frac{E^2_{int}(M1; \omega_N; n \to f; g.s. \to i.s.)}{(\Gamma_n + \Gamma_f + \Gamma^{tot}_{i.s.})^2/4}. \quad (10)$$

Here within the resonant condition the relative probability of nuclear excitation per atomic electron transition $P_{NEET} \simeq E^2_{int}/(\Gamma_n + \Gamma_f + \Gamma^{tot}_{i.s.})^2$ may be relatively large. It means, that the IEB cross-section $\sigma^{(3)}_{dres}$ can be larger than the direct photo excitation cross-section $\sigma^{(1)}_{res}$ under favorable conditions of large values of the corresponding atomic matrix elements. It is no wonder because at isomeric nuclei decay processes the probability of the second- and the third-order processes (internal conversion and electronic bridge) exceeds the probability of the γ-radiation very often.

4. Numerical estimations of the efficiency of nuclear excitation

The ratio ζ of the number of produced isomeric nuclei ^{229m}Th and the number of thorium atoms with nuclei ^{229}Th subjected to irradiation, is given by

$$\zeta \simeq \phi_{L,l}\sigma^{(1,3)}\tau, \quad (11)$$

where $\phi_{L,l}$ is the flux density of the laser (L) or lamp (l) photons, and τ is the irradiation time (it is assumed that τ is smaller than the half-life time of the nuclear isomeric state $T^{i.s.}_{1/2}$).

The half-life $T^{i.s.}_{1/2}$ depends on the decay channel and varies as a function of energy, $E_{i.s.}$. It was calculated in [5, 6]. A preliminary estimation of the isomer half-life is: $10\,s \leqslant T^{i.s.}_{1/2} \leqslant 40\,h$ for decay via electronic bridge, which should dominate under reasonable conditions in the range of $2.5\,eV \leqslant E_{i.s.} \leqslant 4.5\,eV$.

Now we can calculate ζ in eq. (11). All estimations will be made for a typical laser with power 100 mW and special lamp with power 1 kW. Let us estimate the induced activity for a sample of ^{229}Th with mass 1 μg ($\simeq 10^{15}$ nuclei). Thorium atoms can be placed by a very thin layer, on the substructure with diameter 1mm, or frozen into the optically transparent crystal matrix of a noble gas.

For the case $T^{i.s.}_{1/2} \simeq 10\,s$ it is necessary to put $\tau \simeq 10\,s$. We obtain $\zeta \simeq 10^{-2}$ and an induced activity $\simeq 10^{12}$ Bq for laser beam resonance excitation via the IEB process. If we expose a target by the special lamp beam, we obtain the following results: $\zeta \simeq 10^{-6}$ and induced activity $\simeq 10^8$ Bq for the direct photoexcitation process, and $\zeta \simeq 10^{-4}$ and induced activity $\simeq 10^{10}$ Bq for the IEB process.

For the case of large $T^{i.s.}_{1/2}$ we can expose the target during a longer time ($\tau \simeq 10^2$–10^3 s) and reach the value $\zeta \simeq 0.1$–1 for the efficiency of excitation if the discrepancy Δ does not exceed 0.1 eV.

In the first experiments it may be recommended to use a lamp with a suitable spectrum, or an ultraviolet tunable laser, and to look for a resonance condition around the known atomic E1-transition from the ground state to the intermediate one with the energy $32\,666\,sm^{-1}$ (≈ 4.05 eV) or $\lambda_L \approx 306.2$ Å. This transition has a large radiative width $\Gamma^r_A \approx 10^{-8}$ eV [9]. There are plenty of other suitable levels with a known structure and energies up to 5.7 eV [8].

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References

1. Reich, C. W. and Helmer, R. G., Phys. Rev. Lett. **64**, 271 (1990).
2. Helmer, R. G. and Reich, C. W., Phys. Rev. **49**, 1845 (1994).
3. De Mevergnies, M. N., Phys. Rev. Lett. **29**, 1188 (1972).
4. Akovali, Y. A., Nucl. Data Sheet, **58**, 555 (1989).
5. Tkalya, E. V., Yad. Fiz. **55**, 2881 (1992) [Sov. J. Nucl. Phys. **55**, 1611 (1992)]; Pis'ma Zh. Eksp. Teor. Fiz. **55**, 216 (1992) [JETP Lett. **55**, 211 (1992)].
6. Strizhov, V. F. and Tkalya, E. V., Zh. Eksp. Teor. Fiz. **99**, 697 (1991) [Sov. Phys. JETP **72**, 387 (1991)].
7. Tkalya, E. V., Zh. Eksp. Teor. Fiz. **100**, 379 (1992) [Sov. Phys. JETP **75**, 200 (1992)]; Nucl. Phys. **A539**, 209 (1992).
8. Blaise, J. and Wyart, J.-F., "Energy Levels and Atomic Spectra of Actinides", International Tables of Selected Constants **20**, 8, 412 (1992).
9. Corliss, C. H. and Bozman, W. R., "Experimental Transition Probabilities For Spectral Lines Seventy Elements" (Nat. Bur. Stand. Monograph, Washington D.C. 1962), vol. 53, p. 415.