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TRIGGERING OF NUCLEAR ISOMERS VIA DECAY OF AUTOIONIZATION STATES IN ELECTRON SHELLS (NEET)

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Триггерное девозбуждение ядерных изомеров при распаде автоионизационных состояний в электронной оболочке (NEET)

Возбуждение ядер при распадах в электронной оболочке (NEET) может быть использовано для разрядки изомерных состояний ядер (triggering) только при условии компенсации разности энергий (ΔE) и мультипольностей (ΔL) ядерных и электронных переходов. Показано, что использование автоионизационных состояний (AS) позволяет компенсировать ΔE и ΔL. Для возбуждения AS с энергией 10–15 эВ и возбуждения изомера ^{229m}Th (3,5 эВ) посредством NEET при распаде AS может эффективно использоваться лазерное излучение. Пучки ионов, электронов и рентгеновское излучение могут быть использованы для возбуждения AS с энергией до 150 кэВ с последующим девозбуждением изомеров посредством NEET. Для образования AS с энергией 150 кэВ необходимо образовать две или более дырки во внутренних электронных оболочках. Сечение образования таких двухдырочных состояний с помощью пучков ионов может быть достаточно большим. Обсуждаются возможности NEET при рападе AS для возбуждения и девозбуждения ядерных изомеров.

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Triggering of Nuclear Isomers via Decay of Autoionization States in Electron Shells (NEET)

Nuclear excitation by an electron transition (NEET) may be used for triggering of the nuclear isomers decay only when there are compensations between energies (ΔE) and multipolarities (ΔL) of nuclear transition and transition in electron shell. It is shown that using of the autoionization states (AS) allows one to compensate ΔE and ΔL differences. The laser radiation may be used for excitation of AS with energies up to 10–15 eV and ^{229m}Th (3.5 eV) nuclear isomers excitation by NEET via AS decay. The ion beams, electron beams and X-rays may be used for the excitation of the trigger nuclear levels with energies up to 150 keV by NEET via AS and triggering of the nuclear isomers decay. For excitation of AS with the energies up to 150 keV the states with two or more holes in deep inner electron shells must be excited. The cross section for such two-holes states excitation in electron shells by ion beams may be sufficiently high. The possibilities of NEET via AS for triggering of nuclear isomers decay are discussed.

The investigation has been performed at the Flerov Laboratory of Nuclear Reactions, JINR.

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1. AUTOIONIZATION STATES

It is very attractive to use nuclear excitation by an electron transition [1–3] (NEET) because of high cross section for electron shells excitation in different processes. The process consists in that the electron shell excitation energy is transferred to the nucleus without photon radiation. But for effective NEET scheme realization it is necessary to compensate the differences in the multipolarity and energy between electron shell and nuclear transition. One of the possible mechanisms of such a compensation of using NEET via autoionization states was suggested in [4].

Autoionization states (AS) are unstable, related to ionization of atomic state (escape of electron), with two or more excited electrons [5, 6]. AS are the quasi-stationary states and were observed as resonances. For external electron shells excitation AS are well-known and were observed practically for all elements up to Pu [7, 8]. Multistep laser excitation schemes [5] may be very effective for AS excitation with energies up to 15 eV. For internal electron shells excitation AS may have energies up to 10–150 keV and electron or ion impact may be used for such AS excitation. For internal electron shells excitation AS practically were not studied. Because of electron–electron interaction at the AS decay one electron simultaneously escapes from atom (ionization) and the other one goes to the ground state by photon emission (electron shell transition). At suitable conditions instead of photon emission the nuclear excitation by an electron transition (NEET) may take place. For NEET via AS decay the excitation energy is distributed between emitted electron and NEET (similar as energy is distributed between electron and antineutrino in β^- decay). Emission of e^- may compensate the difference in the energy and multipolarity for NEET and it is not necessary to have the precise coincidence between energy and multipolarity of electron shell transition and nuclear transition.

As an example, let us consider the AS of two electrons atoms or ions connected with configurations $nlnl$' and $n = 2$. The energy of such states ($E_{AS,n=2} \approx -Z^2/4$) is higher than the energy of single charged ion ($E \approx -Z^2/2$) and $nlnl$' states with $n = 2$ are the unstable AS states. Due to electron–electron interaction AS may decay (Fig. 1) with simultaneous escape of one electron from atom and other electron transition to $1s$ state.

For electron configuration $2s^2$ we will have $^1S^+$ autoionization state, for $2s2p$ configuration — $^{1,3}P^-$ AS states and for $2p^2$ — $^1S^+$, $^1D^+$, $^3P^+$ AS states.

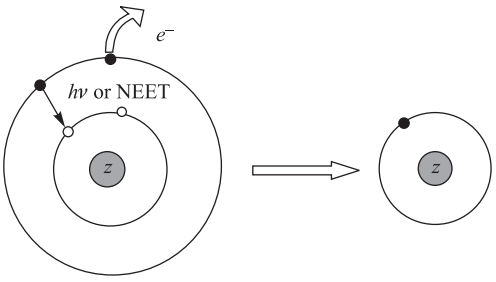

Fig. 1. Scheme of autoionization states (AS) structure and decay. Simultaneously one electron escapes from atom (ionization) and the other one goes to the ground state by photon emission or by transfer of the energy to the nucleus without radiation (NEET). Emission of e^- may compensate the difference in the energy and multipolarity for NEET

Electron–electron interaction mixed $^1S^+$ states from $2s^2$ and $2p^2$ configurations and one of $^1S^+$ (with more weight of $2s^2$ configuration) AS will have the lowest energy and other ^{1}S$^+$ (with more weight of $2p^2$ configuration) AS will have the highest energy.

The decay width Γ is different for different AS and weekly depends on Z. For the lowest $^1S^+$ AS state $^1D^+$ and $^1P^-$ AS states $\Gamma \approx 0.2$ eV. For the highest $^1S^+$ and $^3P^-$ AS states $\Gamma \approx$ (0.02–0.005) eV. Decay of $^3P^+$ AS states to $1s$ state is forbidden as $E1$ and its decay width may be much smaller compare to other AS. So, the width and half-life for AS may change in wide range and $\Gamma \leqslant 0.2$ eV, $T_{1/2} \geqslant 10^{-14}$ s.

2. NEET VIA AS IN eV REGION (^{229m}Th 3.5 eV ISOMER EXCITATION)

The scheme of the autoionization states excitation using laser radiation is presented in Fig. 2. Ionization potential (IP) for Th is 6.08 eV. Using three-step excitation scheme ($h\nu_1 + h\nu_2 + h\nu_3 \leqslant 12$ eV) it is possible to study NEET via AS for nuclear isomers with excitation energy $E \leqslant 6$ eV.

^{229}Th is believed to have a nuclear ground state corresponding to the 5/2$^+$ [633] rotational band head [9] and a low-lying (3.5 $\pm$ 1 eV) isomer [10] corresponding to the 3/2$^+$ [631] rotational band head. ^{229m}Th 3.5 eV isomer is indicated in the decay schemes of ^{233}U, ^{229}Pa and ^{229}Ac [11]. Decay schemes of ^{229}Pa and ^{229m}Th energy [11] are shown in Fig. 3.

^{229m}Th can decay by direct $M1$ photon emission (nuclear light) to the ground state or by alpha decay to ^{225}Ra. It is hard to predict quantitatively $T_{1/2}$ and partial widths for isomer decay. Alpha-decay measurements indicate that if the isomer exists, its half-life must be $T_{1/2} \leqslant 6$ h or $T_{1/2} \geqslant 20$ d [12]. Theoretical estimations for $M1$ photon emission depend on nucleus–electron interaction and

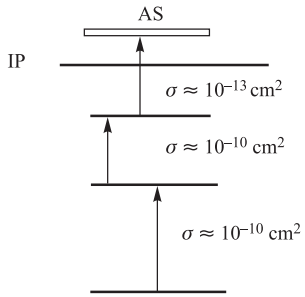

Fig. 2. Three-step scheme of autoionization states (AS) excitation in atom using laser radiation. Efficiency of AS excitation in atoms during three synchronized lasers pulses $\geqslant 10\%$

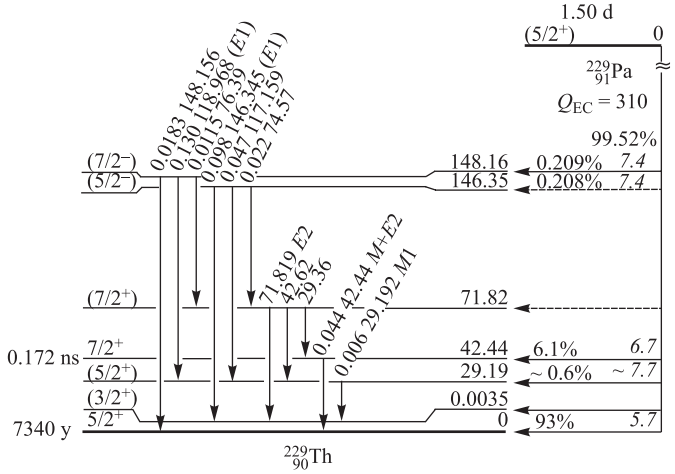

Fig. 3. ^{229}Pa decay scheme [11] and ^{229m}Th energy

isomeric state energy. The results are: $T_{1/2} \approx 3$ s–9 min [13] and $T_{1/2} \approx$ 20–200 h [10]. Up to now, there is no direct evidence for the identification of ^{229m}Th.

^{229m}Th 3.5 eV isomer is a good candidate for nuclear isomer excitation by NEET via AS. For AS excitation three-step laser scheme plan is to be used (Fig. 2). We plan to find optimal scheme for NEET isomer excitation via AS. Isomer will be excited only at definite laser radiation wavelengths and its decay may be detected with high selectivity. Only when three-lasers radiation wavelengths are in resonance with ^{229}Th atomic transition one may observe signal from ^{229m}Th decay with proper half-life.

For NEET via AS the energy of emitted electron (E_e^*), AS excitation energy ($E_{\rm AS}$), ionization potential (IP), electron energy (E_e), when instead of NEET photon with energy $E_{h\nu}$ is emitted, and isomer excitation energy ($E_{\rm NEET}$) are connected as

$$E_{\rm AS} - {\rm IP} - E_e^* \approx E_{\rm NEET}, \tag{1}$$

$$E_{h\nu} + (E_e - -E_e^*) \approx E_{\rm NEET}. \tag{2}$$

Due to electron emission for NEET the differences between $E_{h\nu}$ and $E_{\rm NEET}$ may be compensated. Electron emission may also compensate the differences in multipolarity between electron shell transition and nuclear transition. For $M1$ nuclear transition (^{229m}Th) it is not necessary to compensate multipolarity, because for NEET the proper AS (for which $E1$ transition is forbidden, similar to $^3P^+$ AS) may be used.

3. NEET VIA AS IN keV REGION (^{178m2}Hf ISOMER TRIGGERING)

When the direct transition between initial (isomeric) and final state has a low probability, excitation to the intermediate (trigger) state may deexcite the isomeric state. The trigger level may be excited by X-ray [14–21] and X-ray triggered gamma emission may take place in the process of initial-to-intermediate-to-final state transitions. One of the perspective directions for trigger-level excitation is to use Coulomb excitation [22].

^{178m2}Hf 31-year isomer is interesting for triggering because of its high energy accumulation (1.2 excitation energy 2.445 MeV) and pure gamma-burst applications (stable ground state).

The autoionization states in electron shell may be used for an intermediate (trigger) nuclear-level excitation in NEET via AS [4]. For ^{178m2}Hf isomer the possible trigger levels may be near 10 and 100 keV [14–21]. Autoionization states excitation in the 10–150 keV energy region and NEET process may solve the problem of ^{178m2}Hf isomer triggering. In the case of NEET via AS the compensation of the energy and multipolarity differences, due to specific of NEET via AS, may play a key role.

For excitation of the AS in the 10–150 keV energy region it is necessary to create two or more holes in internal electron shells of Hf atoms or ions. Simultaneous emission of one electron and transition of the second electron to the atomic ground state without photon radiation (NEET) at AS decay may compensate the differences in energy and multipolarity with the corresponding energy transformation into the excitation of a nuclear intermediate state (NEET via AS). Schematic diagram showing the triggering emission of γ-ray driven by NEET via AS is presented in Fig. 4 (initial-to-AS-to-intermediate-to-final state transitions).

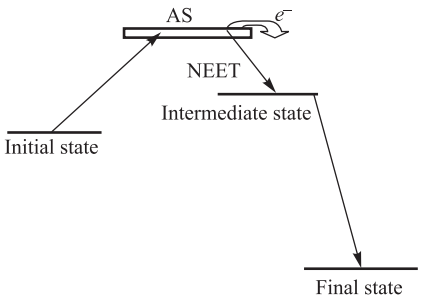

Fig. 4. Scheme of NEET via AS triggered gamma emission

For AS excitation in internal electron shells the electron or ion impact may be used. Now there is no detailed experimental data on AS excitation in internal electron shells for atoms containing nuclear isomers and the findings of effective mechanism of such AS excitation may allow one to make the next step in triggered gamma-emission processes study and applications both for ^{178m2}Hf and other long-lived isomers. One of the ways is the multiple-electron transfer-capture in collisions of highly charged ions with atoms and molecules.

The other problem — the capacity for mass producion of ^{178m2}Hf — remains a question at this moment [23, 24].

Excitation of the AS by ion beams may be sufficiently high [25–29]. Process

$$A^{q+} + B \rightarrow A^{(q-r)+} + B^{(r-n)+} + ne^-, \tag{3}$$

where B — the target atom, A^{q+} — ion with charge q, has the following properties [25–29]:

1. For collision energy (1–100)q eV the multiple-electron transfer-capture cross section significantly depends on the collision energy and projectile species.

2. For collision energies keV/u — cross section does not depend greatly on the collision energy and is nearly the same for the projectile species with the same q. Type of electron shell configuration involved in the process depends on q, type of species and collision energy.

3. Single and double capture of the outermost target electrons are the dominant processes.

4. In the process (3) electron ($ne^- = 1e^-$) may be emitted through autoionization states or directly.

Typical dependence of the electron capture cross section on the initial charge state of the beam ions is presented in Fig. 5 [25]. In Fig. 5 the presented cross sections are summarized over all electron shells.

Partial cross sections [26] from different electron shells are presented in Table.

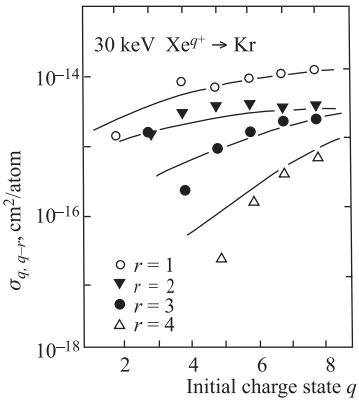

Fig. 5. Total electron capture cross sections for 30 keV Xe^{q+} ions incident on Kr [25]

Cross sections for processes $q+, (q-r), (r-n), n$ in collisions q = 5: Ar^{5+} + Ar = $Ar^{(q-r)+}$ + $Ar^{(r-n)+}$ + ne^-. $E = 1.8q$ keV [26]. T — AS excited in target, P — AS excited in projectile, (dash) – AS did not excite. In the process (3) electron (n = 1) may be emitted through autoionization states (*) or directly (**)

Process (j)	Model σ^j (Å^2) partial	AS	$q \rightarrow (q$–r, r–n, $n)$	Model σ (Å^2) total	Experiment σ (Å^2) total
10000	17.6	–	5 → 4,1,0	28.2	26
01000	6.9	–	5 → 4,1,0		
00100	2.3	–	5 → 4,1,0		
00010	0.8	–	5 → 4,1,0		
00001	0.6	–	5 → 4,1,0		
11000	* * 10.9	–	5 → 4,2,1	10.9	7.8
10100	3.6	–	5 → 3,2,0		
10010	1.3	–	5 → 3,2,0		
10001	0.9	–	5 → 3,2,0	11.7	9.2
01100	3.6	–	5 → 3,2,0		
01010	1.3	–	5 → 3,2,0		
01001	1.0	–	5 → 3,2,0		
00110	* 1.3	T	5 → 3,3,1	9.2	8.4
00101	* 1.0	T	5 → 3,3,1		
00011	* 1.0	T	5 → 3,3,1		
11100	* 3.6	P	5 → 3,3,1		
11010	* 1.3	P	5 → 3,3,1		
11001	* 1.0	P	5 → 3,3,1		
00111	* 1.0	T	5 → 2,4,1	1.0	0.9
01011	1.0	–	5 → 2,3,0		

For two-holes production the string (j) = (l, 0, 1, 0, 0, 0) characterises a process in which the electron of index 1 (this is the electron with binding energy I_1 on the target) and the electron of index 3 (i. e. the electron with binding energy I_3) are captured by A, $I_1 < I_2 < I_3 \ldots$, while the other electrons remain on the target B. Within the model, the string (j) characterises the process uniquely. In general, there are C_r^N different processes in which r electrons ($r = 2$ for two-holes production) are captured out of N available target electrons. These processes lead to different electron configurations on A and B. The unresolved cross section for capture of r electrons is:

$$\sigma_{q-r} = \sum_{(j)} \sigma_{q-r}^{(j)}, \tag{4}$$

where the sum runs over the different strings, (j).

Experimental and theoretical data [26] for the processes $q+, (q-r), (r-n), n$ in collisions $q = 5$: $Ar^{5+} + Ar = Ar^{(q-r)+} + Ar^{(r-n)+} + ne^-$. $E = 1.8q$ keV is presented in Table.

From data on high-charge ion collision with atoms the following conclusion may be done [25–29]:

1. Single and double captures of the outermost target electrons are seen to be the dominant processes.

2. Autoionisation of the projectile following double capture starts around $q = 5$, additional contribution arises around $q = 7$.

3. Autoionisation following triple capture has a similar threshold to autoionisation following double capture.

4. The principal quantum number of the capture electrons increases with q.

5. Projectile autoionisation is much more probable than target autoionisation.

6. Target autoionisation is predicted for recapture of two electrons and loss of at least two or three electrons by the target atom; for instance, for (j) = (0, 0, 1, 1, 1, 0) in collisions with $q > 4$. The corresponding cross sections are of the order of 10^{-16}cm^2.

For isomers triggering by NEET via AS decay the following estimations may be done: corresponding AS excitation cross sections are of the order of 10^{-16}cm^2, beam intensity 10^{12} ions/s, target 10^{13} atoms (3 ng ^{178m}Hf), efficiency [30–32] of NEET not less than 10^{-7}. In this case, we will have more than 100 isomers triggering per second.

CONCLUSION

Nuclear excitation by an electron transition (NEET) via autoionization states (AS) may be an effective instrument for both nuclear isomers excitation and for

triggering of γ-ray emission and depopulation of isomers driven by NEET via AS. For eV isomer excitation (^{229m}Th) the laser radiation may be effectively used for proper AS excitation with high efficiency and selectivity. For the triggering emission of γ-ray driven by NEET via AS it is necessary to find an effective way to excite AS in 10–150 keV energy region. One of the possible ways is to use the ion beams for AS excitation.

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