СЕНСОРИ ТА ІНФОРМАЦІЙНІ СИСТЕМИ

SENSORS AND INFORMATION SYSTEMS

PACS 32.80.Rm, 05.45.+b; UDC 535.42.,539.184
DOI http://dx.doi.org/10.18524/1815-7459.2017.4.119611

AN ADVANCED LASER PHOTOIONIZATION SEPARATION SCHEME FOR RADIOACTIVE ISOTOPES AND PRODUCTS OF ATOMIC ENERGETICS: URANIUM AND THE TRANSURANIUM ELEMENTS

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Abstract. We present an advanced, optimal laser-photoionization scheme of separating heavy radioactive isotopes and nuclear isomers, in particular, the uranium isotopes and the transuranium elements. The advanced scheme is based on the selective laser excitation of the isotope atom into the highly-excited Rydberg states and further electric field ionization mechanism. Some preliminary data for the autoionization resonance characteristics for U and transuranium isotopes are obtained. An appreciable dependence of the reorientation decay velocity of the autoionization resonances at an electric field is analyzed. Two autoionization resonances decay channels are predicted as well as the effect of the giant autoionization resonance width broadening in the relatively weak electric field for uranium and transuranium elements. Using the optimal laser action model and density matrices formalism it has been carried out modelling the optimal scheme of the *U* isotopes separation. It is presented The optimal scheme γ– laser on quickly decayed nuclear isomers with using laser photoionization sorting excited nuclei with autoionization and electric field ionization mechanisms.

Keywords: laser photoionization method, highly radioactive isotopes, new spectroscopy of autoionization resonances for uranium, optimal scheme of isotope laser separation

УДОСКОНАЛЕНА ЛАЗЕРНО-ФОТОІОНІЗАЦІЙНА СХЕМА ПОДІЛЕННЯ РАДІОАКТИВНИХ ІЗОТОПІВ ТА ПРОДУКТІВ АТОМНОЇ ЕНЕРГЕТИКИ: УРАН ТА ТРАНСУРАНОВІ ЕЛЕМЕНТИ

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Анотація. Запропонована нова, оптимальна схема лазерно-фотоіонізаціонного поділення важких радіоактивних ізотопів і ядерних ізомерів, зокрема ізотопів урану і трансуранових елементів. Покращена схема заснована на селективному лазерному збудженні атомів радіоактивного ізотопу у високозбуджені рідбергівські стани і автоіонізаційоному механізмі іонізації в присутності слабкого електричного поля. Отримані деякі попередні дані для енергій автоіонізаційних резонансів для U і трансуранових ізотопів. Представлена залежність швидкості розпаду резонансів в слабкому постійному електричному полі. Прогнозуються два канали розпаду автоіонізаційних станів і передбачений ефект гігантського розширення автоіонізаційних резонансів в спектрі урану у відносно слабкому електричному полі, що вказує на принципово нову спектроскопію автоіонізаціонних станів для урану і трансуранових елементів. Використовуючи оптимальну модель лазерного впливу і формалізм матриць густини, проведено моделювання оптимальної схеми поділу ізотопів U. Представлена оптимальна схема гамма-лазера на ядерних ізомерах, що швидко розпадаються, з використанням лазерно-фотоіонізаційної схеми поділення (сортування) збуджених ядер і подальшої автоіонізації в присутності електричного поля.

Ключові слова: лазерний фотоіонізаційний метод, високо радіоактивні ізотопи,
нова спектроскопія автоіонізаційних резонансів для урана, оптимальна схема лазерного поділення ізотопів

УСОВЕРШЕНСТВОВАННАЯ ЛАЗЕРНО-ФОТОИОНМИЗАЦИОННАЯ СХЕМА РАЗДЕЛЕНИЯ РАДИОАКТИВНЫХ ИЗОТОПОВ, ПРОДУКТОВ АТОМНОЙ ЭНЕРГЕТИКИ: УРАН И ТРАНСУРАНОВЫЕ ЭЛЕМЕНТЫ

В. Б. Терновский, А. В. Глушков, А. В. Смирнов, А. А. Кузнецова, О. Ю. Хецелиус, В. В. Буяджи

Аннотация. Предложена новая, оптимальная схема лазерно-фотоионизационного разделения тяжелых радиоактивных изотопов и ядерных изомеров, в частности изотопов урана и трансурановых элементов. Улучшенная схема основана на селективном лазерном возбуждении атомов изотопа в высоковозбужденные ридберговские состояния и автоионизационном механизме ионизации в присутствии слабого электрического поля. Получены некоторые предварительные данные для энергий автоионизационных резонансов для U и трансурановых изотопов. Представлена зависимость скорости распада автоионизационных резонансов в слабом постоянном электрическом поле. Прогнозируются два канала распада автоионизационных состояний и предсказан эффект гигантского уширения атвоионизационных резонансов в спектре урана в относительно слабом электрическом поле, что указывает на принципиально новую спектроскопию автоионизационных резонансов урана и трансурановых элементов. Используя оптимальную модель лазерного воздействия и формализм матриц плотности, проведено моделирование оптимальной схемы разделения изотопов U. Представлена оптимальная схема гамма-лазера на

быстро распадающихся ядерных изомерах с использованием лазерно-фотоионизационной схемы разделения (сортировки) возбужденных ядер и последующей автоионизации в присутствии электрического поля.

Ключевые слова: лазерный фотоионизационные метод, высоко радиоактивные изотопы, новая спектроскопия автоионизацийних резонансов для урана, оптимальная схема лазерного разделения изотопов»

1. Introduction

Search of the effective, optimal methods and technologies for the radioactive isotopes and nuclear isomers (products of the atomic energetics) detection and separation and also obtaining especially pure substances at atomic level remains one of the very actual problem of modern atomic and nuclear physics, nuclear technologies and atomic energetics [1-4]. These topic is of a great importance because of the increasing development of the modern nuclear energetics. Nuclear power currently despite the known progress is potentially extremely dangerous area, especially in emergency situations like the Chernobyl accident or accident at Japanese NPP "Fukushima. Obviously, the problem of radiation and ecological safety of nuclear power are generated spontaneously formed structure currently used nuclear power cycle (look Figure 1 [1]) , according to which in its final stage of waste nuclear fuel to stand for 50 years in storage, encapsulate, disposed on or after 10 years of aging in nuclear storage facilities sent for recycling [1-4]. The latest comes usually only to radiochemical regeneration of spent U, when: (i) from it is extracted Pu, isolated minor actinides (Np, Am, Cm) and fission products, classifying them as high-level waste, (ii) high-level waste is immobilized, (iii) retain for 50 years in ground conditions and (iv) disposed in geological formations [1-4]. Then extracted (energy) Pu and U regenerated are sent for storage for future use for the production of mixed U-Pu-fuels. One of the schemes of such open nuclear fuel cycle is analyzed in detail in review [2]. It should be recalled that the use of power Pu as dividing components in the U-Pu-fuel complicates number of reasons, including the danger of his treatment in the clear and the threat of uncontrolled proliferation, and certainly sub-optimal isotopic composition, the need of accumulation and long-term storage of Pu etc. Because of these circumstances, now generally in enterprises processed only 10-15% of spent nuclear fuel, which is discharged, and the rest are sent to long-term storage and direct burial that according to various estimates (see [1]), annually output increases the amount of circulation U to 10-12 thousand tons.

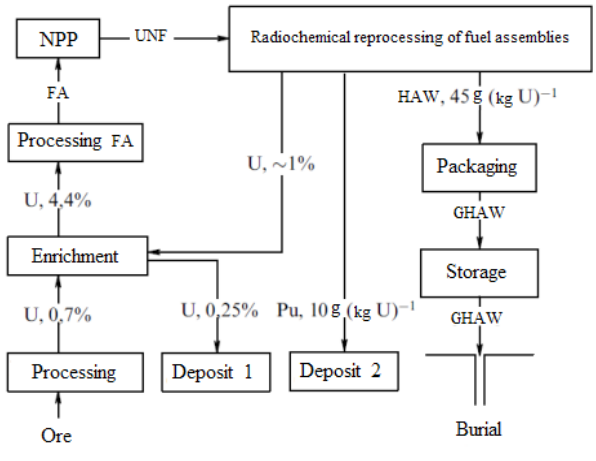

Figure 1. Scheme of open nuclear power cycle. For the U concentration specified isotope ^{235}U . For Pu and high-level waste were given their content in the spent nuclear fuel from WWER-1000.

One of the most promising ways to reduce radiation hazards, in particular, the so-called nuclear transmutation [1-4]. This is the transmutation of radioactive waste transmutation of long-lived fission products, transmutation of actinides, which can be done either in reactors of various types and, in principle, the so-called subcritical power and nuclear plants that have increased compared to conventional reactors nuclear safety. These questions are being continued studied intensively. This issue is being dedicated to a great number of works, because, obviously, the fundamental solution to the problem of destruction of long-lived radioactive waste fission products from spent nuclear fuel will undoubtedly contribute to further development of safe nuclear energy. In a light of saying, the effective technologies of detection

and separation of the heavy radioactive isotopes are critically important [1-10]. The basis for its successful realization is, at first, carrying out the optimal multi stepped photo-ionization schemes for different elements and, at second, availability of enough effective UV and visible range lasers with high average power (Letokhov, 1977, 1979, 1983; etc) [2,3]. The standard laser photo-ionization scheme may be realized with using processes of the two-step excitation and ionization of atoms by laser pulse. The scheme of selective ionization of atoms, based on the selective resonance excitation of atoms by laser radiation into states near ionization boundary and further photo-ionization of the excited states by additional laser radiation, has been at first proposed and realized by Letokhov et al (Letokhov, 1969, 1977) [2]. It represents a great interest for laser separation of isotopes and nuclear isomers. The known disadvantage of two-step laser photoionization scheme a great difference between cross-sections of resonant excitation σ_{exc} and photo-ionization σ_{ion}. It requires using very intensive laser radiation for excited atom ionization. The same is arisen in a task of sorting the excited atoms and atoms with excited nuclei in problem of creation of γ -laser on quickly decayed nuclear isomers. Originally, Goldansky and Letokhov (1974) (see also [2]) have considered a possibility of creating a γ -laser, based on a recoilless transition between lower nuclear levels and shown that a γ -laser of this type in the 20-60 keV region is feasible. These authors has estimated the minimal number of excited nuclei required for obtaining appreciable amplification and possibility of producing sufficient amounts of excited nuclei by irradiation of the target with a thermal neutron beam or by resonant γ -radiation. It is important that low-inertia laser selection of a relatively small friction of excited nuclei of a given composition from the target by the two-step method of selective laser photoionization of atoms with excited nuclei by the radiation from two lasers is principally possible. But, it is obvious that here there is a problem of significant disadvantage of the two-step selective ionization of atoms by laser radiation method. The situation is more simplified for autoionization resonance's in the atomic spectra, but detailed data about characteristics of these levels are often absent (Letokhov, 1977, 1983; Glushkov & Ivanov, 1986, 1992) [2-7]. The key problems here are connected with difficulties of theoretical studying and calculating the autoionization resonance characteristics. Several new optimal schemes for the laser photo-ionization sensors of separating heavy isotopes and nuclear isomers are proposed [2-7]. These schemes are is based on the selective laser excitation of the isotope atoms into excited Rydberg states and further AC, DC electric field ionization or collision mechanisms with using the models [8-16].

In this paper we present an advanced, optimal laser-photoionization scheme of separating heavy radioactive isotopes and nuclear isomers, in particular, the uranium isotopes and the transuranium elements. The advanced scheme is based on the selective laser excitation of the isotope atom into the highly-excited Rydberg states and further electric field ionization mechanism. Some preliminary data for the autoionization resonance characteristics for U and transuranium isotopes are obtained. An appreciable dependence of the reorientation decay velocity of the autoionization resonances at an electric field is analyzed. Two autoionization resonances decay channels (traditional Beutler-Fano channel and new Letokhov-Ivanov channel) are predicted as well as the effect of the giant autoionization resonance width broadening in the relatively weak electric field for uranium and transuranium elements. Using the optimal laser action model and density matrices formalism [7-12], it has been carried out modelling the optimal scheme of the U and Np and Pu isotopes (nuclei) separation.

2. Laser photoionization separation of heavy radioactive isotopes (uranium and transuranium elements): Qualitative aspects

Let us remind that in a classic scheme the laser excitation of the isotopes and nuclear isomers separation is usually realized at several steps: atoms are resonantly excited by laser radiation and then it is realized photo ionization of excited atoms. In this case photo ionization process is characterized by relatively low cross section $\sigma_{ion}=10^{-17}$-10^{-18}cm^2 and one could use the powerful laser radiation on the ionization step. This is not acceptable from the energetics point of view [2].

The alternative mechanism is a transition of atoms into Rydberg states and further ionization by

electric field or electromagnetic pulse. As result, requirements to energetic of the ionized pulse are decreased at several orders. The main feature and innovation of the presented scheme is connected with using the DC electric field (laser pulse) autoionization on the last ionization step of the laser photoionization technology. There is a principal difference of the simple ionization by DC electric filed. The laser pulse ionization through the auto ionized states decay channel has the advantages (more high accuracy, the better energetics, universality) especially for heavy elements and isotopes, where the DC electric field ionization from the low excited states has not to be high effective. This idea is a key one in the realization of sorting the definite excited atoms with necessary excited nuclei of the A^+ kind, obtained by optimal method of selective photo-ionization of the A kind atoms at the first steps. The suitable objects for modeling laser photoionization separation technology are the radioactive isotopes of Cs, I, U and the long-lived transuranium elements etc. These isotopes are the most dangerous especially in the light of emergency situations like the Chernobyl accident or accident at Japanese NPP "Fukushima. We considered a scheme for the laser separation and sensing the uranium and thulium isotopes. All necessary excitation and ionization constants for solution of the density matrice equations system are calculated within above described model and methods [5-10]. The laser photoionization scheme for *U* isotopes included the following steps: i). Laser excitement of the ^{235}U isotopes from the ground $5f^36d7s^2$-$^5L_6^o$ state and low lying metastable $5f^36d7s^2$-$^5K_5^o$ state with energy 620,32 см$^{-1}$; The final step is the autoionization of the Rydberg excited atoms by a laser pulse or DC electric field pulse ionization and output of the created ions. The scheme will be optimal if an atom is excited by laser radiation to state, which has the decay probability due to the autoionization (pulse ionization) higher than the radiation decay probability. So, one could guess that the accurate data on the autoionization states energies and widths and the same parameters for the DC Stark resonances are needed. The consistent and accurate theoretical approach to calculation of these characteristics is based on the operator perturbation theory formalism and corresponding advanced relativistic version [5-16].

3. Relativistic model of autoionization decay of heavy atoms in a DC electric field

Probability of the ionization (autoionization width) for highly excited atoms by electric field is given by the full flow of probability through the plane, which is perpendicular to z-axe. Calculation of the probability requires a solution of the axially symmetrical problem, when a potential barrier separates two classically allowed regions. The examples of the application of such problem are an atom in a uniform electric field, the two-centre problem etc. Let us find the wave function in the below-barrier region. In this case, the wave function is localized in the vicinity of the most probable tunnelling way, that is the potential symmetry axis z. For the bi-spinor

$$\psi = \begin{pmatrix} \xi \\ \eta \end{pmatrix}, \tag{1}$$

the Dirac equation has the following form:

$$\begin{aligned} c\bar{\sigma}\rho\xi &= (E - V + c^2)\eta, \\ c\bar{\sigma}\rho\xi &= (E - V - c^2)\xi \ . \end{aligned} \tag{2}$$

Inserting first equation of the system (2) into second one and using substitution

$$\begin{aligned} \xi &= (W^+)^{1/2}\Phi, \\ W^{\pm} &= E - V \pm c^2 \end{aligned} \tag{3}$$

we obtain the second-order equation

$$\Delta\Phi + K^2\Phi = 0$$

$$K^2 = \frac{1}{\hbar^2 c^2}\left[(E-V)^2 - c^4\right] - \frac{\Delta V}{2W^+} - \frac{3}{4}\left(\frac{\bar{\nabla}V}{W^+}\right) + \frac{i}{W^+}\bar{\sigma}\left[\bar{\nabla}V, \bar{\nabla}\right]. \tag{4}$$

Since the potential is axially symmetrical, we seek a solution to' this equation in the cylinder system of co-ordinates as follows:

$$\Phi = \begin{pmatrix} F_1(z,p)\exp\left[i(m-1/2)\varphi\right] \\ F_2(z,p)\exp\left[i(m+1/2)\varphi\right] \end{pmatrix}. \tag{5}$$

Substituting (5) into (4) gives the matrix equation:

$$(\Delta + \partial)F = (\hbar^{-2}q^2 + \gamma)F, \qquad F = \begin{pmatrix} F_1 \\ F_2 \end{pmatrix} \tag{6}$$

$$q = \frac{1}{c}\left[c^4 - (E-V)^2\right]^{1/2},$$

$$\partial = \frac{1}{W^+}\left(\frac{\partial V}{\partial p}\frac{\partial}{\partial z} - \frac{\partial V}{\partial z}\frac{\partial}{\partial p}\right)\begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix}$$

$$\gamma = \begin{pmatrix} a_{m-1/2} & b_{m+1/2} \\ b_{m-1/2} & a_{-m-1/2} \end{pmatrix},$$

$$a_\mu(z,p) = \frac{\mu^2}{p^2} + \frac{1}{W^+}\left[\frac{\mu}{\rho}\frac{\partial V}{\partial p} + \frac{\Delta V}{2} + \frac{3}{4}\frac{(\bar{\nabla} V)^2}{W^+}\right],$$

$$b_\mu(z,p) = -\frac{\mu}{pW^+}\frac{\partial V}{\partial z} \quad .$$

A solution for system (6) is found numerically on the basis of the finite differences numerical algorithm [5]. In a case of atomic ionization by the pulsed field, probability of process is defined by the following expression:

$$W(nlm) = \sum_{n2}(a_{n1n2}^{nlm})^2 W(n_1 n_2 m) . \qquad (7)$$

Here $W(n_1n_2m)$ is the state decay probability; a are the coefficients of expansion of the $\psi(nlm)$ functions on the parabolic functions $\psi(n_1n_2m)$. In real multi-electron atom it is necessary to account for the influence of the electron shells, which results in the changing the potential barrier and wave functions. To define the wave functions and electron state energies in an electric field, one needs to carry out the diagonalization of energy matrice, calculated between states with the same n [5-8]. The diagonalization of the complex energy matrix leads to complex energy correction: ReE -iΓ/2 , where Re E is the level shift and Γ is the level width, including the radiation and autoionization widths simultaneously. If the effects of the autoionization resonance decay are included in the matrix M, then Γ presents only the autoionization width of the state. Only Re M is diagonalized. The imaginary part is converted by means of the matrix of eigen-vectors $\{C_{mk}\}$ The eigen vectors are obtained by diagonalization of ReM:

$$\text{Im } M_{ik} = \sum_{ij} C^*_{mi} M_{ij} C_{jk} . \qquad (8)$$

The other details of calculation procedure are given in refs. [7-16].

4. Some numerical results and concussions

Here we present some key results of numerical calculating the ionization characteristics for heavy isotope of the uranium and thulium and modelling the optimal scheme parameters of the laser photoionization sensor. In figure 2 we present our calculation results on the critical electric field strength in dependence upon effective quantum number n^* for atom of U. The points in the figure correspond to the experimental data, solid line 1 is a theoretical estimate based on the classical relation (E~ 1/16 n^4 ; Stark shift of the level and tunneling of the electron are not taken into account) , solid line 2 - calculation by formula [2] for a pulsed electric field; the dotted line is the results of this calculation. It is stressed that the hydrogen-like approximation gives an inaccuracy 15-20% (see [5-8]). At the same time consistent relativistic calculation has given the results in an excellent agreement with experiment. The same situation takes a place for the transuranium isotopes of Np and Pu. The most interesting feature of the ionization in an external electric field is connected with an effect of electric field on the autoionization resonances in the heavy isotopes (the last step of the laser photoionization scheme).

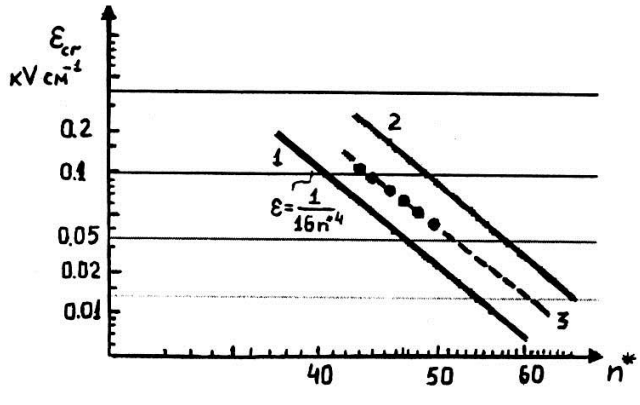

Figure 2. Dependence of the critical electric field strength on the effective principal number for U: points - experiment; solid line 1 - theoretical evaluation based on classical considerations; solid line 2 - calculation on the basis of Letokhov-Ivanov formula; the dotted line is the present work [2,5-8].

Table 1 illustrates the calculated energies (in cm^{-1}) of the levels of the higher members of the Rydberg series of uranium, counted from the level of 32899.790 cm^{-1}; excitation sequence: 6056.81+6098.10+(5880-5890)Å $5f^37s^2np$. (experimental data from [17]).

Table 1

The calculated energies (in cm^{-1}) of the levels of the higher members of the Rydberg series of uranium, counted from the level of 32899.790 cm^{-1}; excitation sequence: 6056.81+6098.10+(5880-5890)Å $5f^37s^2np$ ($5f^37s^2nf$)

E_{exp} [9]	Our data	$n^*_{\exp}$	n^*_{theor}
49878.5	49878.3	37.13	42
49882.5	49882.2	38.10	43
49886.6	49886.2	39.18	44
49890.2	49889.8	40.20	45
49893.6	49893.1	41.25	46
49896.6	49896.1	42.24	47
49899.4	49899.1	43.24	48
	49901.8	44.23	49
	49904.2	45.25	50
	49906.7	46.25	51
	49908.8	47.23	52

Note: $n^*=\{R/[\text{limit-(level value)}]\}^{1/2}$

It is very much important to note that one of the most detailed papers on the uranium Rydberg spectra contains data to be reconsidered. This topic will be presented in the separate paper. Further we have calculated the energies and widths for higher members of the uranium Rydberg series (members accessed from 32.899,79 cm^{-1} level). Excitation sequence: 6056,81+6098,10+(5880-5890) Å. For *$5f^37s^2np$ (n=40-44)* levels the following results are obtained: i). For ε=0 *V*×cm^{-1}, configuration *$5f^37s^242p$, E*=49877,49 (experimental value [17]: 49877,5); *$\Gamma(5f^37s^242p)$*=1,794D-01; *$\Gamma(5f^37s^242s)$=2*,702D-05; ii). For ε = 100 *V*×cm^{-1}; *$\Gamma(5f^37s^242p)$*=1,675D-01; *$\Gamma(5f^37s^242s)$=5*,913D-04. So, we have here a strong change of the autoionization resonance width at a moderately weak electric field too. At first this new spectroscopic effect has been discovered for the lanthanides atoms (see [5]). Detailed spectroscopic information about autoionization resonances is needed to optimize the excitation and ionization of the atom. An optimal scheme presumes a compromise between high excitation probability and high decay rate that determines the lower and upper boundaries for the autoionization resonances decay rate. The use of the ROD channel essentially increases the possibilities of such a compromise. It is very important for carrying out the optimized scheme of the selective photoionization sensor.

Further we present the results of numerical modelling the optimal scheme parameters of the laser photoionization sensor. As usually, the optimization procedure of the laser photoionization sensor scheme is in a searching the optimal form of the laser pulse to provide a maximum of excited particles in the gases separation scheme (naturally this is one of the possible versions). The separation process is described by the density matrice equations system (c.f. [5-8]). In figure 3 we present the results of numerical modelling the optimal form of laser pulse in the laser photoionization sensor scheme for the uranium isotopes. The following notations are used: δ pulse + dotted line is the optimal form of the laser pulse; curves (1) x_1 and (2) x_2 are the populations of the ground and excited (n=42) states. In the qualitative relation obtained data are similar to data for other *Na, Rb* and *Tm* isotopes (see [5-10] and Refs. therein).

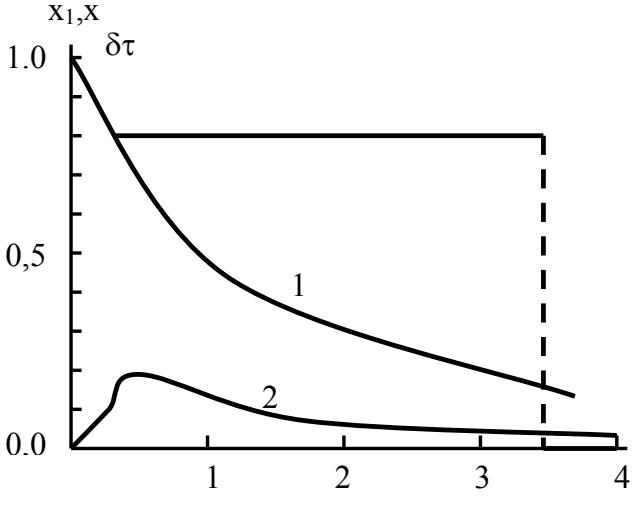

Figure 3. Results of modelling the U isotopes separation process by the laser photo-ionization method (δ+dashed – laser pulse optimal form; see text).

The δ-pulse provides maximum possible level of excitation (the excitation degree is about ~0,25; in experiment (Letokhov, 1983) with rectangular pulse this degree was ~ 0,1). Using δ-pulse indeed provides a quick ionization, but the ionization yield will be less than 100% because of the sticking on intermediate levels. So, from energetic point of view, this type of ionization can be very perspective alternative to earlier proposed classical two-step and more complicated photoionization schemes (Letokhov, 1983) [2]. The similar situation and analogous conclusions are obtained for

the Tm and Yb isotope separation with the corresponding difference in the energetic and radiative characteristics data. So, one can say here about sufficiently optimal scheme of the separating highly radioactive isotopes and products of atomics energetics such as U and others. The key features of the corresponding scheme (technology) are based on the selective laser excitation of the isotopes atoms to the excited Rydberg autoionization states and further autoionization decay in a presence of a weak DC electric pulse ionization. This scheme is supposed to be very effective in solving the modern actual problems of the transmutation of radioactive elements and decreasing the energy loses in the modern atomic energetics cycles [1-6]. One should also note that the considered scheme can be easily implemented to the possible advanced scheme of the γ - laser on quickly decayed nuclear isomers with using laser photoionization sorting excited nuclei M^*_{k+1} with autoionization mechanism through the Rydberg states [5-7]. Figure 4 illustrates the principal moments of this scheme. It generalizes the known Goldansky-Letokhov (Goldansky & Letokhov, 1974) and other (Baldwin et al, 1981; Glushkov et al 2010) schemes and has to be more efficient especially from energetics point of view.

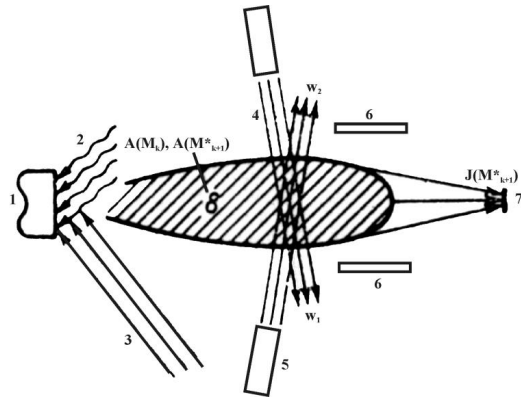

Figure 4. The optimal scheme γ - laser on quickly decayed nuclear isomers with using laser photoionization sorting excited nuclei M^*_{k+1} with laser excitation, autoionization and electric field ionization mechanisms: 1 – target of atoms M_k; 2- flux of slow neutrons; 3 – laser ray for evaporation of target; 4 – laser ray for the first step excitation of atoms with excited nucleus $A(M^*_{k+1})$; 5 – laser ray for second-step excitation to highly excited atomic states and Rydberg autoionization by electromagnetic field; 6 – collector system; 7 - atoms with excited nucleus $A(M^*_{k+1})$; 8 – flux of evaporated atoms.

The laser photo ionization scheme with autoionization of the highly excited atoms (with optimal set of energetic and radiative parameters: pulse form, duration, energetic for laser and electric field pulses etc.) could provide significantly more high yield and effectiveness of the whole process of the isotope separation. It is especially worth for implementation to the possible principal scheme of γ -laser on quickly decayed nuclear isomers with autoionization sorting the excited atoms.

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Стаття надійшла до редакції 01.12.2017 р.

PACS 32.80.Rm, 05.45.+b; UDC 535.42.,539.184
DOI http://dx.doi.org/10.18524/1815-7459.2017.4.119611

AN ADVANCED LASER PHOTOIONIZATION SEPARATION SCHEME FOR RADIOACTIVE ISOTOPES AND PRODUCTS OF ATOMIC ENERGETICS: URANIUM AND THE TRANSURANIUM ELEMENTS

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Summary

The aim of the work is to develop and present a new effective approach to problem of detection and separation radioactive isotopes (radionuclides), which is based on a new physical principles and to carry put computing of spectroscopic parameters and modelling the optimal separation scheme for the U and transuranium isotopes.

We present an advanced, optimal laser-photoionization scheme of separating heavy radioactive isotopes and nuclear isomers, in particular, the uranium isotopes and the transuranium elements. The advanced scheme is based on the selective laser excitation of the isotope atom into the highly-excited Rydberg states and further electric field ionization mechanism. Some preliminary data for the autoionization resonance characteristics for U and transuranium isotopes are obtained. An appreciable dependence of the reorientation decay velocity of the autoionization resonances at an electric field is analyzed. Two autoionization resonances decay channels are predicted as well as the effect of the giant autoionization resonance width broadening in the relatively weak electric field for uranium and transuranium elements. Using the optimal laser action model and density matrices formalism it has been carried out modelling the optimal scheme of the *U* isotopes separation. It is presented The optimal scheme γ - laser on quickly decayed nuclear isomers with using laser photoionization sorting excited nuclei with autoionization and electric field ionization mechanisms.

Keywords: laser photoionization method, highly radioactive isotopes, new spectroscopy of autoionization resonances for uranium, optimal scheme of isotope laser separation

PACS 32.80.Rm, 05.45.+b; УДК 535.42.,539.184
DOI http://dx.doi.org/10.18524/1815-7459.2017.4.119611

УДОСКОНАЛЕНА ЛАЗЕРНО-ФОТОІОНІЗАЦІЙНА СХЕМА ПОДІЛЕННЯ РАДІОАКТИВНИХ ІЗОТОПІВ ТА ПРОДУКТІВ АТОМНОЇ ЕНЕРГЕТИКИ: УРАН ТА ТРАНСУРАНОВІ ЕЛЕМЕНТИ

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Реферат

Метою роботи є розробка та представлення нового ефективного підходу до проблеми детектування та розділення радіоактивних ізотопів (радіонуклідів), що базується на нових фізичних принципах, та проведенні обчислень спектроскопічних параметрів та моделювання параметрів оптимальної схеми поділення для урана та трансуранових ізотопів.

Запропонована нова, оптимальна схема лазерно-фотоіонізаціонного поділення важких радіоактивних ізотопів і ядерних ізомерів, зокрема ізотопів урану і трансуранових елементів. Покращена схема заснована на селективному лазерному збудженні атомів радіоактивного ізотопу у високозбуджені рідбергівські стани і автоіонізаційоному механізмі іонізації в присутності слабкого електричного поля. Отримані деякі попередні дані для енергій автоіонізаційних резонансів для U і трансуранових ізотопів. Представлена залежність швидкості розпаду резонансів в слабкому постійному електричному полі. Прогнозуються два канали розпаду автоіонізаційних станів і передбачений ефект гігантського розширення автоіонізаційних резонансів в спектрі урану у відносно слабкому електричному полі, що вказує на принципово нову спектроскопію автоіонізаціонних станів для урану і трансуранових елементів. Використовуючи оптимальну модель лазерного впливу і формалізм матриць густини, проведено моделювання оптимальної схеми поділу ізотопів U. Представлена оптимальна схема гамма-лазера на ядерних ізомерах, що швидко розпадаються, з використанням лазерно-фотоіонізаційної схеми поділення (сортування) збуджених ядер і подальшої автоіонізації в присутності електричного поля.

Ключові слова: лазерний фотоіонізаційний метод, високо радіоактивні ізотопи,
нова спектроскопія автоіонізаційних резонансів для урана, оптимальна схема лазерного поділення ізотопів