UDC 535.42

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LASER PHOTOIONIZATION ISOTOPE SEPARATION TECHNOLOGY AND NEW PRINCIPAL SCHEME FOR γ-LASER ON QUICKLY DECAYED NUCLEAR ISOMERS WITH AUTOIONIZATION SORTING OF HIGHLY EXCITED ATOMS

Optimal scheme of the laser photo-ionization heavy isotopes (isomers) separation technology and the new possible principal scheme of γ -laser on quickly decayed nuclear isomers with autoionization sorting the highly excited heavy atoms are presented.

To number of the very actual problem of modern nuclear technology, quantum and photoelectronics is related a search of the effective methods for isotopes and nuclear isomers separation and obtaining especially pure substances at atomic level. 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 [1–27]. 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 (c.f. ref.[1]). 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} ($[\sigma_{exc}/\sigma_{ion}]>10^4\div10^8$). 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 [1,2].

Originally, Goldansky and Letokhov [3,4] has considered a possibility of creating a γ -laser, based on a recoiless transition between lower nuclear levels and shown that a γ -laser of this type in the 20–60 keV region is feasible. A feature of design is operation based on relatively short-lived isomer nuclear states with lifetime of 0,1 to 10 sec. The authors [3] 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 [1,2]. The situation is more simplified for autoionization resonance's in the atomic spectra, but detailed data about characteristics of these levels are often absent (c.f.[2,4,5,12,17]). The key problems here are connected with difficulties of theoretical studying and calculating the autoionization resonance characteristics. In [2,3] it has been presented principally new approach to solving a class of problems treated. In ref. [2,3,14,19–23] new optimal schemes for the laser photo-ionization sensors of separating heavy isotopes and nuclear isomers were proposed. It is based on the selective laser excitation of the isotope atoms into excited Rydberg states and further autoionization and DC electric field ionization mechanisms. To carry out modelling the optimal scheme of the *U* and *Tm* isotopes (nuclei) sensing, the optimal laser action model and density matrices formalism (c.f.[2,14,19–22]) were used. The similar schemes of laser photo ionization method are developed for control and cleaning the semiconductor substances [19]. The optimal laser photo-ionization schemes for preparing the films of pure composition on example of creation of the 3-D hetero structural super lattices (layers of $Ga_{1-x}Al_xAs$ with width 10E and GaAs of 60E) have been proposed and new models of optimal realization of the first step excitation and further ionization of the Ga^+ ions in Rydberg states by electric field are calibrated. In this paper we give the further development of approach to construction for the optimal schemes of the laser photo-ionization isotope separation technology and to creation of new possible principal scheme of γ -laser on quickly decayed nuclear isomers with laser autoionization or electromagnetic field ionization sorting the excited atoms.

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 [1]). 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 modelling laser photoionization separation technology are the isotopes of alkali element Cs, lanthanides and actinides. We considered the isotopes of $_{55}Cs^{133}_{78}$ and $_{70}Yb^{171}_{101}$. For example, the resonant excitation of the Cs can be realized by means dye lasers with lamp pumping (two transitions wavelengths are: $6^2S_{1/2}\rightarrow 7\ ^2P_{3/2}$ 4555A and $6^2S_{1/2}\rightarrow 7\ ^2P_{1/2}$ 4593A) [15]. In table 1 there are listed the energy parameters for different states of the caesium, obtained in the different approximations (from refs. [1,2,23]). It is useful to remind the corresponding hyperfine splitting energy ($6\ ^2S_{1/2}$, transition 4–3) of Cs: exp. data- $\Delta\nu(F,F')= 9192{,}64$MHz ; $\Delta E(F,F')= 306{,}630\cdot 10^{-3}$ cm^{-1} ; theor. data [23] -$\Delta\nu(F,F')= 9177{,}80$MHz ; $\Delta E(F,F')= 306{,}135\cdot 10^{-3}$ cm^{-1} (from ref.[23]).

Table 1

Valent electron ionization energies (in atom. units) of the ^{133}Cs: ε^{RHF} –one-configuration Hartree-Fock data, релятивистского ХФ; $\varepsilon^{RHF}+\delta\varepsilon^{RHF}$ — the same data, but with account for the correlation corrections; ε^{QED} — QED perturbation theory data; ε^{Exp}- experimental data (see text)

State	ε^{RHF}	$\varepsilon^{RHF}+\delta\varepsilon^{RHF}$	ε^{QED}	ε^{Exp}
$6s_{1/2}$	0,12737	0,14257	0,14295	0,14310
$6p_{1/2}$	0,08562	0,09198	0,09213	0,09217
$6p_{3/2}$	0,08379	0,08951	0,08960	0,08964
$7s_{1/2}$	0,05519	0,05845	0,05862	0,05865
$7p_{1/2}$	0,04202	0,04385	0,04391	0,04393
$7p_{3/2}$	0,04137	0,04303	0,04309	0,04310

The next step is in the further excitation to the Rydberg S,P,D states with main quantum number n=31–37 (the optimal value n=35). Final step is the autoionization of the Rydberg excited atoms by a electromagnetic field pulse 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 bigger than the radiation decay probability. In figure 1 we present the numeric modelling results of the optimal form of laser pulse in the photoionization scheme with auto-or electric field ionization by solving the corresponding differential equations system [2,3,14,19–22]. The following definitions are used: δ+dashed line is corresponding to optimal form of laser pulse, curves 1 and 2 are corresponding to populations of the ground and excited states of Cs. The δ -pulse provides maximum possible level of excitation (the excitation degree is about ~0,25; in experiment [1] with rectangular pulse this degree was ~ 0,1). It is in great degree similar to analogous scheme with the DC electric field and stochastic collisional ionization mechanisms [3,15,21,22]. In fig.1 there is also presented the typical behaviour of the ground (curve 1) and highly excited (curve 2) states population. Let us remember data regarding the excitation and the ionization cross sections for studied system: the excitation cross section at the first step of the scheme is ~10^{-11}cm^2; the ionization cross-section from excited 7^2P_2 state: $\sigma_2=10^{-16}$cm^2, from ground state $\sigma_2=10^{-18}$cm^2 [1]. One can see that the relation of these cross sections is 10^5 and 10^7 correspondingly. This fact provides the obvious non-efficiency of standard photoionization scheme.

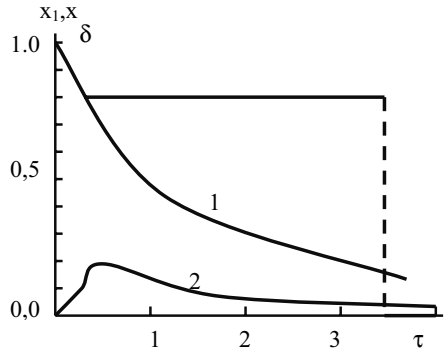

Fig.2. Results of modelling Cs isotopes separation process by the laser photo-ionization method (δ+dashed — laser pulse optimal form; see text)

A use of the autoionization mechanisms at the final step for ionization of the Rydberg excited atoms provides more optimal scheme from energetic point of view. For example, for the $35^2S_{1/2}$ transition the corresponding cross section can reach the value ~10^{-13}cm^2. 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 (c.f.[3,19–21]). More suitable situation takes a place for the for Yb isotope separation. It is very important that the proposed 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. Fig.2 easily explains the principal moments of this scheme. It generalizes the known Goldansky-Letokhov [4] and other [2,9,21,22] schemes and has to be more efficient especially from energetics point of view. In this context it is worth to remind very impressive results of the last years, connected with engineering atomic highly excited Rydberg states and correspondingly cooperative laser-gamma-muon-electron- nuclear states (transitions) with the laser (and raser) pulses [24–30]. It is quite possible that cited new effects can be realized in the tasks considered here.

So, 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.

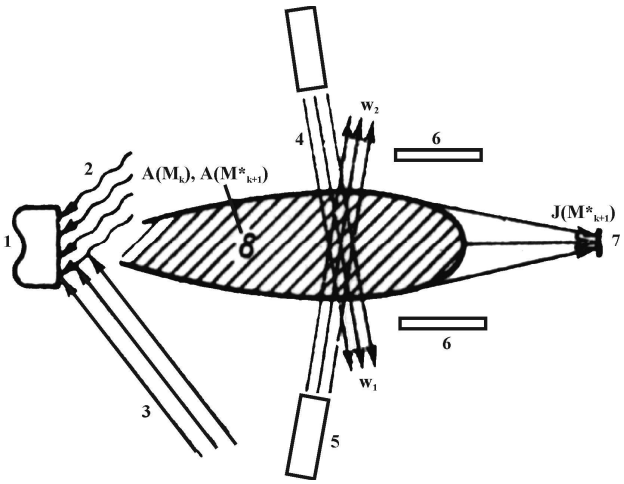

Fig.1. Possible scheme γ — laser on quickly decayed nuclear isomers with using laser photoionization sorting excited nuclei M^*_{k+1} with electric field and auto- and electric field ionization mechanisms: 1 — target of atoms M_k; 2- flux of slow neutrons; 3 — laser ray for evaporation of target; 4 — 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;

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Abstract
Optimal scheme of the laser photo-ionization heavy isotopes (isomers) separation technology and the new possible principal scheme of γ -laser on quickly decayed nuclear isomers with autoionization sorting the highly excited heavy atoms are presented.
Key words: laser photoionization, isotopes separation, γ -laser on quickly decayed nuclear isomers

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ЛАЗЕРНО-ФОТОИОНИЗАЦИОННАЯ ТЕХНОЛОГИЯ РАЗДЕЛЕНИЯ ИЗОТОПОВ И НОВАЯ ПРИНЦИПИАЛЬНАЯ СХЕМА γ -ЛАЗЕРА НА БЫСТРОРАСПАДАЮЩИХСЯ ЯДЕРНЫХ ИЗОМЕРАХ С АВТОИОНИЗАЦИОННОЙ СОРТИРОВКОЙ ВЫСОКО ВОЗБУЖДЕННЫХ АТОМОВ

Резюме
Предложены новая схема лазерно-фотоионизационной технологии разделения тяжелых изотопов (изомеров) и новая возможная принципиальная схема γ -лазера на быстрораспадающихся ядерных изомерах с автоионизационной сортировкой высоко возбужденных тяжелых атомов.
Ключевые слова: лазерная фотоионизация, разделение изотопов, γ-лазер на быстро распадающихся ядерных изомерах

УДК 535.42

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ЛАЗЕРНО-ФОТОІОНІЗАЦІЙНА ТЕХНОЛОГІЯ РОЗПОДІЛУ ІЗОТОПІВ І НОВА ПРИНЦИПІАЛЬНА СХЕМА γ -ЛАЗЕРА НА ЯДЕРНИХ ІЗОМЕРАХ, ЩО ШВИДКО РОЗПАДАЮТЬСЯ, ІЗ АВТОІОНІЗАЦІЙНОЮ СОРТИРОВКОЮ ВИСОКО ЗБУДЖЕНИХ АТОМІВ

Резюме
Запропоновані нова схема лазерно-фотоіонізаційної технології розподілу важких ізотопів (ізомерів) та нова принципіальна схема γ — лазера на ядерних ізомерах, що швидко розпадаються, із авто іонізаційним сортуванням високо збуджених важких атомів.
Ключові слова: лазерна фотоіонізація, розподіл ізотопів, γ- лазер на ядерних ізомерах, що швидко розпадаються