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Converting nuclear energy into the energy of coherent optical radiation

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Abstract

This paper is devoted to the question of the conversion of nuclear energy into the energy of coherent optical radiation. The two possible ways to convert nuclear energy into laser radiation are discussed: direct and combined nuclear pumping. The concept of using laser gas active media capable of working with both direct and combined nuclear pumping is considered. The results of an investigation by Kazakh scientists on nuclear pumped lasers active media on bound–bound atomic transitions are presented.

Keywords: Combined nuclear pumping; Direct nuclear pumped laser; Nuclear reactor; Nuclear-excited plasma

INTRODUCTION

The idea of converting the energy of nuclear reactions into laser radiation appeared immediately after the first optical quantum generators were introduced (Herwig, 1964). The high specific power and compactness of nuclear energy sources, along with other advantages compared with the other traditional methods for ionization and excitation of active laser media, have sufficiently stimulated the interest in the creation and study of nuclear-pumped lasers. Extensive opportunities for the application of nuclear-pumped lasers, especially in the cases where powerful lasers have to be placed on stand-alone remote platforms, have also stimulated research activities in this area.

There are two possible ways to convert nuclear energy into laser radiation: direct and combined nuclear pumping (CNP). Direct nuclear pumping (DNP) is a method of converting nuclear energy, in which the energy of nuclear reactions is directly transferred to be employed in the ionization and excitation of buffer gas atoms and molecules, and is then, within a sequence of plasma-chemical processes, transformed into population inversion and coherent radiation. During CNP, the energy of nuclear reactions is spent for pre-ionization of an active laser medium followed by electric discharge pumping; so electrical energy can be generated in the same nuclear reactor.

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The aim of this paper was to summarize research results related to the conversion of nuclear energy into the energy of coherent light radiation, both by DNP and CNP, as well as to provide information on research activities in this field being performed in Kazakhstan.

There are two possible conventional ways to utilize the energy from nuclear reactions for the ionization and excitation of active media in lasers: by employing surface or volume sources of charged particles (see Fig. 1).

The surface sources are solid coatings of laser tubes' internal surfaces emitting charged reaction products for laser medium excitation or ionization under the influence of neutron flux or due to radioactive decay (where FF_h and FF_l are heavy and light fragments of fission):

$$ {}_{92}U^{235} + {}_0 n^1 \rightarrow FF_h(65\,\mathrm{MeV}) + FF_l(97\,\mathrm{MeV}), \quad (1)$$

$$ {}_7B^{10} + {}_0 n^1 \rightarrow {}_3 Li(0.855\,\mathrm{MeV}) + {}_2 He^4(1.495\,\mathrm{MeV}), \quad (2)$$

$$ {}_3Li^6 + {}_0 n^1 \rightarrow {}_1 H^3(2.73\,\mathrm{MeV}) + {}_2 He^4(2.05\,\mathrm{MeV}), \quad (3)$$

$$ Po^{210} \rightarrow He^4(5\,\mathrm{MeV}) + Pb^{206}. \quad (4)$$

The cross-sections of such reactions for thermal neutrons are sufficiently large and comprise 582 barns (U^{235}), 3837 barns (B^{10}), and 945 barns (Li^6).

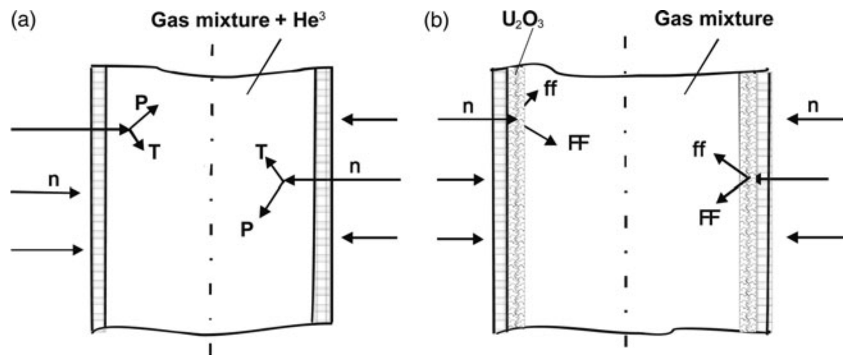

Fig. 1. Volume (**a**) and surface (**b**) sources of charged particles.

Lasing at CO, He-Hg, Ar-Xe, He-Cd, and other laser media has been employing surface sources (Batyrbekov, 2008*a*). However, significant energy loss (>50% of the energy released in nuclear reactions) due to the geometrical factor and the passage of particles through the source itself decreases the overall system efficiency. Surface sources are inefficient at high pressures and at large volumes of laser active media, since the penetration depth for fission fragments in a laser medium is limited in this case, causing heterogeneous ionization of the active medium. Unevenness of active medium ionization leads to a temperature gradient along the diameter of the laser tube, and as a consequence, unevenness of the density of the gas active medium. As a result, a wide angle or focusing lens can appear depending on the ratio of the mean free path of the charged particles and the laser tube diameter, which adversely affects the lasing conditions (Batyrbekov *et al.*, 1994*a*). Despite this, the surface sources are used quite often for nuclear pumping of lasers, especially in the case where it is necessary to avoid the presence of a charged particles volume source in a laser active medium to eliminate the negative effects on population inversion kinetics.

Volumetric sources of charged particles are introduced homogeneously into gaseous working media of lasers. UF_6 can be used as the source; the fission reaction in this case results in high-energy fission fragments for excitation and ionization of the laser medium. However, UF_6 has some negative features, such as strong deactivation of the excited states, a large capacity for absorption of electrons with negative ions formation, chemical activity of atomic fluorine, etc. The gas isotope He^3 that emits protons and tritium after neutron capture can be used most effectively for this purpose:

$$ {}_2He^3 + {}_0n^1 \rightarrow {}_1H^3(0.19\,\text{MeV}) + {}_1H^1(0.57\,\text{MeV}). \quad (5)$$

The cross-section for this reaction is sufficiently large, about 5,400 barns, and the reaction is very successfully used for lasing in certain active media (He^3-Xe, He^3-Cd, He^3-Zn, and others) where He^3 plays the role of a buffer gas, assuring a uniform volumetric excitation of the active medium.

Volume and surface sources of charged particles can both be used simultaneously. For example, the joint use of He^3 and U_2O_3 at the optimum ratio of the laser tube diameter and the active medium pressure provides a more uniform energy distribution in the gas and eliminates the “gas lens” problem. Moreover, arranging the charged particles surface source in staggered order along the laser tube eliminates the problems resulting from distortion of the beam directionality along the laser axis (DeYoung *et al.*, 1989).

PECULIARITIES OF NUCLEAR PUMPED LASERS ACTIVE MEDIA

The only type of laser with successfully implemented nuclear pumping is still the gas laser (DeYoung *et al.*, 1989; Mis’kevich, 1991; Miley, 1993; Batyrbekov, 2008*a*). The use of nuclear energy for pumping liquid and solid-state lasers is limited by the radiation damages problem. At the same time, the gas lasers have features. First, only gas lasers can be transparent in the wide spectral range (from the vacuum UV region to the far-infrared region of the spectrum), and as a consequence, they have a large working range of wavelengths. Second, the operating levels in the gas are the levels of almost isolated particles (atoms, ions, and molecules), which determines the narrowness of laser transitions and makes it possible to achieve a high monochromaticity of laser radiation. Third, the gas atmosphere has much lower density and higher optical homogeneity, so the losses for diffraction and scattering are minimal in it, making it easier to reach the diffraction limit. Gas laser emission has the lowest divergence compared to the liquid and solid-state lasers. However, the relatively low density of gas environments requires sufficient extension of the lasers to meet the amplification conditions, which is not always feasible at the excitation by nuclear reactor energy. Utilization of a multiple-pass resonator makes it possible to eliminate this disadvantage, but introduces additional negative reactivity and some technical difficulties.

There are some publications covering the study of possible applications of solid-state lasers nuclear pumping. In

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particular, the possibility of using a nuclear-excited lamp for pumping solid-state laser is shown (Miley, 1993; Prelas, 1995; Batyrbekov, 1993*a*). The possibility of using a mixture of alkali metals with He^3 as an active medium of the nuclear-excited plasma is considered. In particular, the coefficient of nuclear energy conversion into radiation of Na_2^* excimer molecule can theoretically reach 40%. To resolve the problem of radiation damage in solids, it was proposed to use optical fibers to take nuclear-induced lamp radiation away from the radiation field of the nuclear reactor. Studies with solid-state converters, pumped by radiation from a DNP laser, were performed by All-Russian Scientific Research Institute of Technical Physics, Snezhinsk (VNIITF) (Magda, 2007).

A series of works on the possibilities to use liquids as an active medium in nuclear pumping lasers have been published by the Institute of Physics and Power Engineering, Obninsk (IPPE) (Dobrovolskiy *et al.*, 2003; Kabakov *et al.*, 2007). In one of the options, it was proposed to use inorganic liquids activated by rare earth and actinide elements as the active medium. However, until now there has been no information about obtaining lasing by direct pumping in liquids. Thus, the most promising is the study of gaseous media as active media for nuclear-pumped lasers.

DIRECT NUCLEAR PUMPED LASERS

The first experimental confirmation of the possibility to create a laser with DNP came in 1975, when MacArthur and Tollefsrud succeeded in lasing on vibrational transitions of the CO molecule with $\lambda = 5.1–5.6$ µm using U_2 coatings and a fast pulse reactor of the Sandia-II pool type (McArthyr & Tollefsrud, 1975). Soon, there were reports on lasing with DNP in He-Xe (Fuller *et al.*, 1975) and Ne-N_2 (De Young, 1976) mixtures.

There are currently more than four dozen lasers capable of operating in excitation by the energy of pulsed nuclear reactors and emitting in a wide spectral range from 391 nm to 5.6 µm (Batyrbekov, 2008*a*).

The geography of the studies has also expanded. While in the 1980s lasers with DNP were studied only in the Soviet Union and the United States, Germany (De Young, 1976; Adonin *et al.*, 2006; 2009; Krucken *et al.*, 2007), China (Han-De *et al.*, 1993; Chengde *et al.*, 2007), Japan (Hayashida *et al.*, 1991; Kakuta *et al.*, 1998; Obara & Takezawa, 2007), Brazil (Campus & Shaban, 1997*a*, 1997*b*), and other countries are active in this area today.

The Direct Nuclear Pumped Lasers Program (lasers with DNP) has being successfully developed in the United States of America for many years, with the participation of scientists from Sandia and Los Alamos National laboratories, University of Illinois, Missouri, North Carolina, and others. In the former Soviet Union, the studies of direct nuclear pumped lasers were performed in All-Russian Research Institute of Experimental Physics, Sarov (VNIEP), VNIITF, Moscow Engineering Physics Institute (MEPI), IPPE, Institute of Nuclear Physics of National Nuclear Center of the Republic of Kazakhstan (INP NNC RK), Institute of Atomic Energy of National Nuclear Center of the Republic of Kazakhstan (IAE NNC RK), etc. The first lasing with DNP was achieved in Arzamas-16 (Sarov) in May 15, 1973 (Melnikov *et al.*, 2007), two years before the first announcement made by U.S. scientists, but considering the secrecy of the research the first publication on this topic appeared only in 1979 (Dovbysh *et al.*, 1979*a*; 1979*b*). It was the He-Xe laser with the following parameters: wavelength 2.6 µm, efficiency ≈0.45%, average radiation power ≈25 W, pulse energy ≈60 mJ.

All currently existing direct nuclear pumped lasers can be classified into three main groups: vibrational transitions of molecule lasers; metal vapor ion lasers; and lasers based on neutral atom transitions. It should be noted that this corresponds to the traditional classification of gas lasers into molecular, ion, atomic, and excimer lasers. Lasing with DNP on excimer molecule transitions has not been obtained so far.

DNP LASERS ON VIBRATIONAL TRANSITIONS OF MOLECULES

The characteristic feature of lasers on molecular vibrational-rotational transitions due to the small difference in energy between the working levels is lasing in the mid- and far-infrared range. The typical example of this laser class is CO laser operating on vibrational-rotational transitions in the main electronic state within the 5–6.5 µm wavelength range. A high efficiency, a high output power, and the ability to work in continuous and pulsed modes with different methods of achieving inversion (pumping by an electric beam and electric discharge, gas-dynamic pumping and chemical pumping) naturally stimulated interest in developing CO laser with direct nuclear-pumping.

As is noted above, the laser on vibrational transitions of a CO molecule was one of the first lasers with DNP (McArthyr & Tollefsrud, 1975). However, in contrast to other methods of excitation, in the case of DNP it was not possible to achieve a high efficiency of input energy conversion into coherent electromagnetic radiation. The maximum experimental values of output energy 0.1–0.3 mJ and efficiency 0.1–0.3% from the energy delivered into the gas were obtained at 50 ms duration of generation. Moreover, a high lasing threshold ($\Phi_{thresh} = 5 \times 10^{16}$ n/cm^{2}s), pressure limits, and strict requirements for active medium cooling (laser was operated at 77 K temperature and 100 mTorr active medium pressure) made the direct nuclear pumped CO-laser not interesting in terms of practical applications. A detailed analysis of CO molecule excitation processes was provided in Gudzenko *et al.* (1978) taking into account the function of electron distribution in conditions of nuclear pumping. According to calculations there, the maximum efficiency of the CO laser with DNP does not exceed 0.5% of the energy deposited into gas, which is consistent with the experimental results.

Attempts to obtain lasing on vibrational-rotational transitions of the CO_2 molecule with DNP by analogy with the CO laser were not successful (Batyrbekov, 2008*a*). A detailed explanation of this fact is given in Andriyahin (1972) based on the calculation of the electron distribution function in nuclear-induced plasma of a molecular laser. Kinetics of the CO_2 laser with DNP showed that with the compositions of the mixtures, which are traditionally used in electric-discharge CO_2 lasers, the amplification factors on the vibration–rotation systems of the CO_2 molecule are too small to achieve lasing, primarily due to the significant difference of excitation mechanisms in these two systems. According to Hasan (1980), the CO_2 laser with nuclear pumping can operate at low pressure and low concentrations of CO_2 and N_2. Under these conditions, the CO_2 laser with DNP is not effective, and its conversion to other scales is not possible.

Although a dense He-N_2 mixture was proposed as an active medium for lasers with DNP in 1980, lasing was achieved only in 1996 primarily due to effective population of the B-states N_2^+ in the processes of helium molecular ions recharging on nitrogen molecules. In Grebyonkin & Magda (1991), lasing on the B-X transition (0–0) of a nitrogen molecular ion with $\lambda = 391$ nm has been reported. To our knowledge, this is the shortest-wavelength laser with DNP. The experiments were performed on the pulsed nuclear reactor EBR-L with a thermal neutron flux of $\sim 10^{17}$ n/cm^{2}s with 250 microseconds pulse half-width. The mixture of He-N_2-H_2 was used as the laser active medium. It was possible to achieve laser radiation by selective population of the lower laser level $N_2^+(X)$.

Metal Vapor DNP Ion Lasers

Current DNP ion lasers are lasers in which transitions between the energy levels of metal ions are used as working transitions. This group includes lasers on atomic transitions of Hg^+, Cd^+, and Zn^+ ions. The characteristic feature of this group is the many resonances between the levels of excited buffer gas atoms and the levels of metals ions (since ionization potentials of metals atoms are quite below the ionization potential of He atoms). Therefore, the upper working level is populated at collision processes with excitation energy transferred from metastable helium atoms to metal atoms, followed by ionization of this atom and ion excitation.

These lasers do not require exact resonance of excited He atoms and excited metal ions $(M^+)^*$, like in the case of He-Ne lasers, since the energy excess is carried away by the electron. The ionization process with recharging can also provide population of the upper working levels.

An advantage of metal vapor ion lasers that attracts much interest of researchers in these lasers is the wide range of wavelengths and relatively low threshold of lasing. The He-Hg laser with wavelength $\lambda = 615$ nm (Akerman, 1976; Akerman & Miley, 1977) was the first laser with DNP in the visible range. A laser radiation with wavelength $\lambda = 441.6$ nm achieved in the He^3-Cd laser (Dmitriyev *et al.*, 1980; 1982) has been for a long time the shortest one for direct nuclear pumped lasers. However, there are many technical difficulties imposed by metal vapor lasers due to the high temperature for metal evaporation, corrosion issues and increased requirements on the purity of the used gases. The highest efficiency rates achieved for metal vapor ion lasers with DNP are as follows: He-Hg 10^{-6}% (Akerman, 1976; Akerman & Miley, 1977); He-Cd 0.5% (Dmitriyev *et al.*, 1980); He-Zn 0.06% (Dmitriyev *et al.*, 1982) of the input in gas energy.

DNP Lasers on Neutral Atom Transitions

The typical example of this class of lasers is the He-Ne laser on atomic transitions of neon with $\lambda = 632.8$ nm. However, the low output characteristics of the He-Ne laser have limited the possibilities for its application. The He-Ne laser is used mainly in laboratory conditions and, as a rule, for adjustment purposes.

There is a report available on the creation of a He-Ne laser with DNP (Carter *et al.*, 1980). The paper reported that a continuous laser on the transition of $3p'[3/2]_2$–$5s'[1/2]_1^0$ neon atom with 632.8 nm wavelength was achieved. The measured value of a small-signal amplification factor in the mixture of He^3:Ne = 5:1 at 300 Torr pressure and $\Phi \approx 6 \times 10^{11}$ n/cm^{2}s was 9.81 dB/m. The laser threshold when using the resonator with low *Q*-factor (50% loss per pass) was obtained at $\Phi \approx 2 \times 10^{11}$ n/cm^{2}s. Attempts of other authors to confirm this result have failed (Prelas & Schlapper, 1981; Krucken *et al.*, 2007). In particular, in experiments conducted in the active zone of the stationary nuclear reactor WWR-K at the flows exceeding neutron fluxes for more than two orders of magnitude used in Carter *et al.* (1980), generation has not been achieved even at high *Q*-factor of the resonator.

In 1990, several research groups simultaneously reported on generation with DNP on atomic neon transitions (Hays & Hebner, 1990; Kopai-Gora *et al.*, 1990; Grebyonkin & Magda, 1991; Sinyanskiy, 1995). The lasing was obtained on the transitions $3p'[1/2]_0$-$3s'[1/2]_1$ NeI with $\lambda = 585.2$ nm wavelength ("yellow" neon laser) and $3p[1/2]_1$-$3s[3/2]_1$ and $3s[3/2]_2$ NeI with $\lambda = 724.5$ and 703.2 nm wavelengths ("red" neon lasers), respectively.

The maximum output characteristics of 40 and 9 mJ and 140 and 30 W with an efficiency of 0.16 and 0.02% were obtained for the "yellow" and "red" lasers, respectively. Low threshold characteristics 1.5×10^{13} n/cm^{2}s) have been reported in Miley and Shaban (1993), which corresponds to the capabilities of existing stationary nuclear reactors. However, there is still no experimental confirmation of continuous lasing with DNP in the conditions of the stationary nuclear reactor.

Detailed studies of the kinetics of laser active media based on 3p-3s NeI atom transitions pumped by the weak source of external ionization were first conducted by the staff of the Laboratory of Nuclear Power Installation Physics (LNPIP) of the INP NNC RK (Batyrbekov, 1990; 2008*b*; 2008*c*; Batyrbekov & Danilychev, 1992; Batyrbekov *et al.*, 1990;

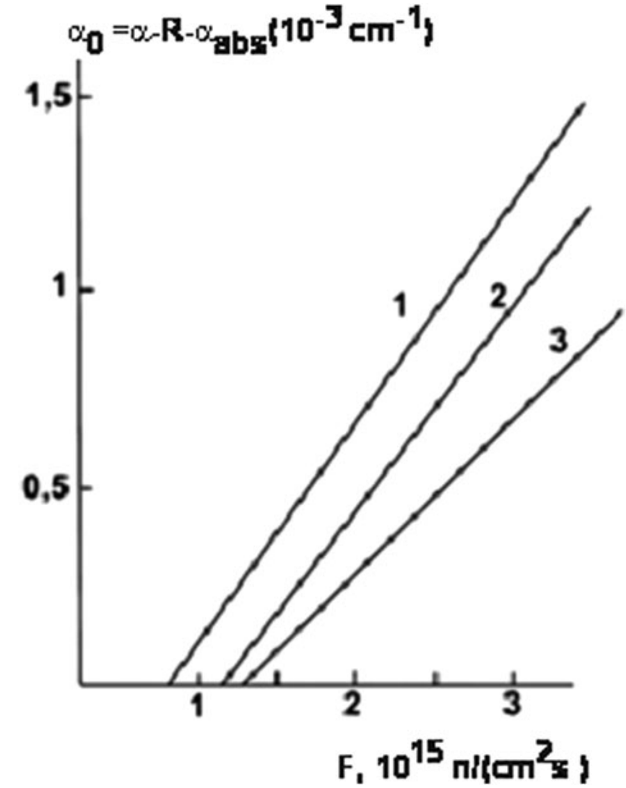

Fig. 2. Dependence of $\alpha_0 = \alpha_{ampl} - P - \alpha_{abs}$ value for the transitions with $\lambda = 585.2$ nm (He^3 (3 atm) + Ne (30 Torr) + Ar (8 Torr)) (**1**), 703.2 nm (Ne (1 atm) + Kr (15 Torr)) (**2**), 724.5 nm (Ne (1 atm) + Kr (35 Torr), (**3**) from the flow of thermal neutrons.

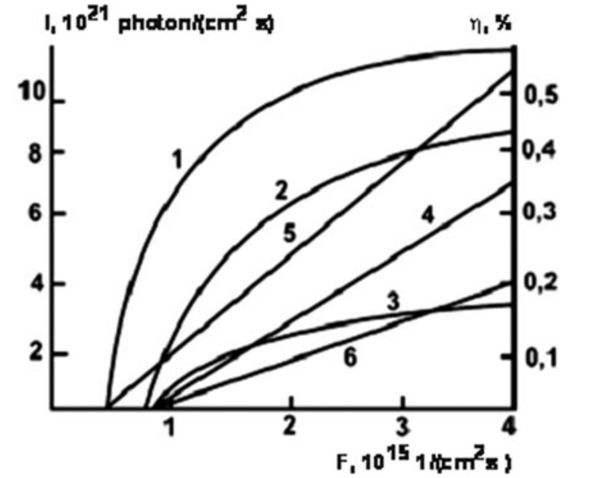

Fig. 3. Dependence of laser radiation density (4,5,6) and efficiency (1,2,3) for $\lambda = 585.2$ (1,4), 703.2 (3,6), and 724.5 (2,5) for the mixtures: He (3 atm) + Ne (30 Torr) + Ar (9 Torr) (1,5), Ne (1 atm) + Kr (20 Torr) (2,4), Ne (1 atm) + Kr (40 Torr) (3,6).

1991; 1994*b*). Spectral studies of an neon plasma were performed in the central channel of the stationary nuclear reactor and in the laboratory using α-particles. The spectral research made it possible to study the effectiveness of population for the upper 3p levels of the neon atom, the processes in the bulk and intermultiplet relaxation of the working laser levels at ionization of the mixture by the products of nuclear reactions. The effect of He and Ne on the effectiveness of neon 3p levels population was studied. It was shown that neon 3p levels population effectiveness in the process of dissociative recombination depends on the degree of vibrational excitation of Ne_2^+ ions.

The subthreshold spectral diagnostics of nuclear excited plasma made it possible to measure the rate constants in the key processes and to understand the mechanisms of inverse population. As seen in Figure 2, the threshold values of thermal neutrons fluxes, that is, the flux at the condition of $\alpha_0 = \alpha_{ampl} - P - \alpha_{abs} = 0$ (where α_{ampl} is the small signal amplification factor, P is the coefficient of useful losses, and α_{abs} is the non-resonant absorption of laser radiation) are $\Phi_{thresh} \approx 4 \times 10^{14}$, 7×10^{14}, and 8×10^{14} n/cm^{2}s, respectively, for the transitions with $\lambda = 585.2$, 703.2, and 724.5 nm. The obtained values confirmed previous findings that lasing at the flux typical of currently existing stationary nuclear reactors is not possible.

The design values of laser radiation and the efficiency of lasers on NeI transitions, such as the functions of thermal neutrons flux value, are shown in Figure 3. The calculations performed for the flux typical of pulsed nuclear reactors are in good agreement with the experimental results.

Lasing with DNP was also obtained on the atomic transitions of other noble gases: Ar, Kr, and Xe. The active laser media are of interest in terms of practical application with significant efficiency at low pumping powers. The mixtures of gases (He, Ne)-Ar-Xe with $\lambda = 1.73$, 2.026, and 2.65 μm wavelength 5d-6p transitions of xenon atom are referred to such media.

Lasing with DNP on xenon atom IR transitions was achieved for the first time in 1975 in the University of Florida in collaboration with the Los Alamos National Laboratory (Fuller *et al.*, 1975). Lasing was produced at the transition 5d $[7/2]_3$-6p$[5/2]_2$ XeI with $\lambda = 3.508$ μm wavelength in the He-Xe mixture. The products of nuclear U^{238}(n,f)F reaction were used as the pumping source.

Since it was one of the first demonstrations of lasing with DNP, relatively low output characteristics (efficiency of ~0.01%) and high threshold (~3×10^{15} n/cm^{2}s) have been achieved. To date, the maximum output power $W \approx$ 2600 W (Koshelev *et al.*, 1990) and the efficiency $\eta \approx$ 2.2–3% (Grebyonkin & Magda, 1991; Alford & Hays, 1990) were obtained at the transition 5d $[3/2]_1$-6p$[3/2]_1$ XeI with $\lambda = 1.732$ μm wavelength. The low threshold flux of thermal neutrons (3.7×10^{13} n/Cm^{2}s) was detected by Voinov and co-workers (Koshelev *et al.*, 1990) for the transition 5d$[3/2]_1^0$-6p$[3/2]_1$XeI with $\lambda = 2.026$ μm wavelength, which indicates the possibility of achieving a continuous steady-state generation in the conditions of the stationary nuclear reactor. In total, lasing was achieved at six atomic 5d-6p xenon transitions (Fig. 4).

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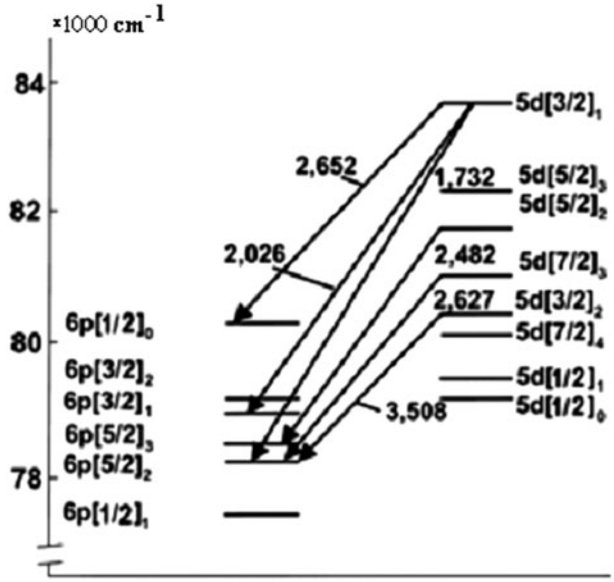

Fig. 4. The diagram of Xe atom transitions.

A significant contribution to the understanding of the kinetics of physical-and-chemical processes occurring in xenon plasma was made by Kazakhstani scientists. The staff of the LNPIP performed comprehensive studies of nuclear-induced plasma of xenon mixtures with noble gases (Batyrbekov, 1987*a*, 2008*a*). Using the results of the spectral investigations, mathematical simulation of the main plasma-chemical processes in nuclear-induced plasma of He-Ar-Xe and Ar-Xe laser mixtures has been performed.

In collaboration with the University of Illinois, for the first time we have achieved lasing at the transition 5d $[3/2]_1$-6p$[3/2]_1$ XeI with $\lambda = 1.732\ \mu m$ wavelength pumped by the products of the $B^{10}(n,\alpha)Li^7$ nuclear reaction (Batyrbekov, 2008*d*; 2009; Batyrbekov *et al.*, 1993*b*; 1995; 1994*c*). The experiments were performed at the TRIGA reactor in the University of Illinois. TRIGA is a pressurized water-type reactor capable of operating either in stationary or pulsed (high pulse repetition frequency) modes. The experiments were performed at the reactor in the pulsed mode with the following parameters: peak power 1600 MW, peak value of thermal neutrons flux $2.5 \times 10^{15}\ n/cm^2s$, and half-height neutron pulse duration 12.1 ms. The scheme of the experiment is shown in Figure 5.

The oscillogram of the laser signal and neutron impulse is shown in Figure 6. A resonator with dielectric mirrors with reflection coefficients of 99.9 and 90.0% at 1.732 μm wavelength was used in the experiments.

The lasing was produced by a thermal neutron flux of $7 \times 10^{14}\ n/Cm^2s$, which corresponds to the specific pumping power of 2.6 W/cm^3. When using the resonator with "zero" losses (99.9%) the value of the threshold thermal neutrons flux is $1 \times 10^{14}\ n/cm^2s$ or 0.44 W/Cm^3, which agrees well with the experimental results of other researchers who

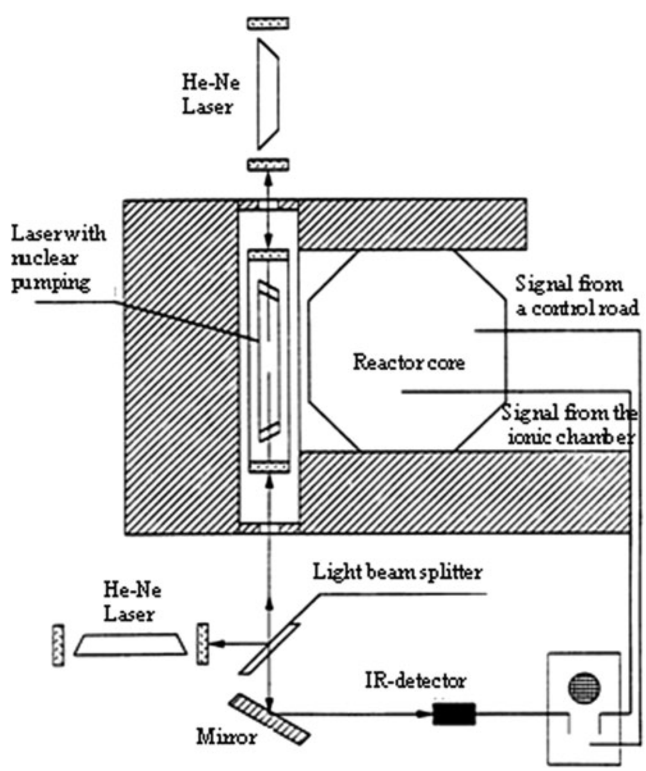

Fig. 5. The scheme of the experiment at the TRIGA reactor (USA).

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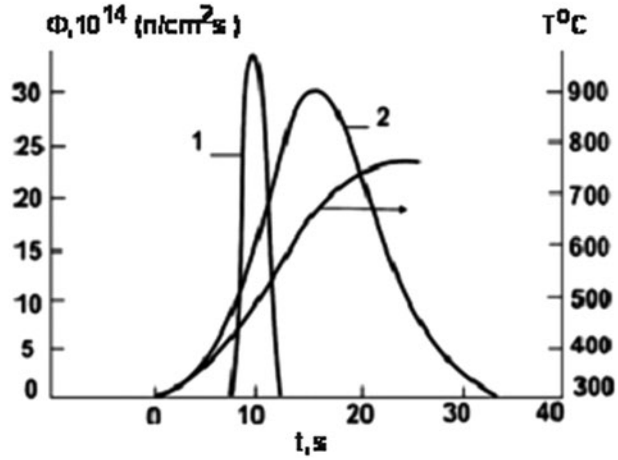

Fig. 6. The oscillogram of generation and neutron impulses. Temperature change of the gas medium (right scale). (**1**) generation; (**2**) neutron impulse (maximum power 523 MW).

used U^{235} fission fragments as a pumping source (Grebyonkin & Magda, 1991), and indicates weak dependence of the mechanism of inverse population on the source of primary ionization (Batyrbekov, 2008*d*).

The relatively high efficiency of lasers on atomic transitions of neon and xenon with DNP stimulated interest in finding new collisional lasers employing the allowed bound–bound (stimulated transition cross-section $\sigma \approx 10^{-13}$–10^{-14}cm^2) electron transitions.

Scientists in Kazakhstan have attained significant progress in this area (Batyrbekov *et al.*, 1987*b*; 1987*c*; 1987*d*; 1988; 1997). We showed that the triplet transitions of the mercury atom are promising for lasing in the visible range. In particular, the high efficiency of population of 7^3S_1 upper working level of the mercury atom was revealed in dissociative recombination of molecular ions formed in the following reaction chain:

$$Xe + ff \rightarrow Xe^+ + ff + e, \quad (6)$$

$$Xe^+ + 2Xe \rightarrow Xe_2^+ + Xe, \quad (7)$$

$$Xe_2^+ + Hg \rightarrow Hg^+ + 2Xe, \quad (8)$$

$$Hg^+ + 2Xe \rightarrow XeHg^+ + Xe, \quad (9)$$

$$XeHg^+ + Hg \rightarrow Hg_2^+ + Xe, \quad (10)$$

$$Hg_2^+ + e \rightarrow Hg\left(7^3S_1; 7^3P\right) + Hg. \quad (11)$$

The measured factor of nuclear energy conversion into radiation at the mercury triplet lines is close to the quantum one, which shows the high selectivity ($\delta = 0.8 \pm 0.2$) of the process (probably by cascade transitions from the 7^3P level). To obtain inverse population, it was proposed to use H_2 or D_2 selectively depleting the lower working 6P-states. The rate constants for the key processes involved in the formation of inverse population were measured (Batyrbekov *et al.*, 1987*b*; 1987*c*; 1987*d*; 1988). The calculations of the main plasma components, threshold and output characteristics of laser radiation indicated the possibility of lasing with DNP at triplet transitions of the mercury atom.

Figure 7 shows the calculated values of the amplification factor excluding the coefficient of useful losses on the resonator and non-resonant absorption of laser radiation. It can be seen that the rated value of the threshold thermal neutrons flux is $\Phi_{thresh} = 1.5 \times 10^{14}$ n/Cm^{2}s for the optimal mixture He^3(2 atm)-Xe(1 atm) Hg(7 Torr)-H$_2$(40 TTrr) for $\lambda =$ 546.1 nm, in terms of the maximum amplification factor.

These conclusions were outstandingly verified in VNIITF (Bochkov *et al.*, 1992). They have achieved generation in the He-Xe-Hg-H$_2$ mixture excited by the products of the U^{235}(n,f)F nuclear reaction at the 7^3S_1-6^3P_2 transition with $\lambda = 546.1$ nm. In particular, the threshold value was $\Phi_{thresh} = 5 \times 10^{14}$ n/Cm^{2}s for the optimal mixture of He(119TTrr)–Xe(119 TTrr)-Hg(6.8 TTrr)-H$_2$(58.9 TTrr) excited by the products of the U^{235}(n,f)F nuclear reaction. The small difference between the theoretical and experimental values of the H$_2$ optimal content can possibly be explained

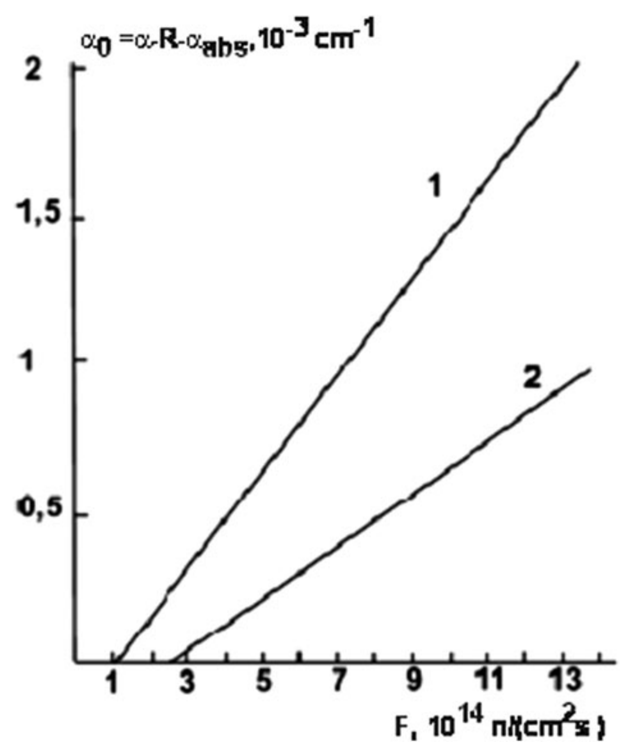

Fig. 7. $\alpha_0 = \alpha - P - \alpha_{abs}$ value versus the flux of thermal neutrons Φ_t for the $\lambda = 546.1$ nm (**1**), 435.8 nm (**2**) transitions for the mixture: He^3 (2 atm) + Xe (1 atm) + Hg (7 TTrr) + H$_2$(40 Torr), He^3 (2 atm) + Xe (1 atm) + Hg (7 TTrr) + H$_2$(33 Torr).

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by the need for additional cooling of the secondary electrons in the experimental conditions (Bochkov *et al.*, 1992). Gases of the same purity used in the experiments have a significant impact on the energy parameters of the laser (Korzenev *et al.*, 2008). In the above kinetic model of the laser, impurities in the active gas mixture were not taken into account.

This is the first and until now the only laser with DNP evolved under the classical sequence of events, that is, preliminary experimental studies, the study of the inverse population mechanism, the creation of the kinetic model, calculations of plasma parameters, the conclusion on the possibility of generation, and only after all these – experimental confirmations — generation. In all other lasers with DNP, transitions verified with other sources of hard ionization, such as an electron beam, were used as laser transitions (Fedenev *et al.*, 1995).

COMBINED NUCLEAR-PUMPED LASERS

Employing electric discharge for the pumping in lasers with CNP, when the energy of nuclear reactions is spent only for ionization of the laser active medium, it is possible to achieve high power transferred into the active medium — several orders of magnitude higher than in the case of DNP at the same flux of thermal neutrons. The increase in power delivered to the laser active medium makes it possible to achieve lasing with a shorter wavelength and at the transitions with "short life" upper laser levels, as in the case of excimer molecules.

When the neutron flux of the stationary nuclear reactor is used to stabilize the discharge, no problem related to separating foil mechanical strength appears; such problems are typical of discharge lasers stabilized by electron beams. The sources of ionizing particles are arranged in the working volume of the laser, and the penetrating power of neutrons through the walls of the laser chamber is high. Accordingly, the structural strength imposes no restriction on the pulse repetition rate. Volumetric ionization sources such as He^3 or $^{235}UF_6$ in the working gas would homogeneously ionize large volumes of working mixtures (tens to hundreds of liters) at high pressures. The continuous ionization of the working mixture in the nuclear reactor eliminates the need to harmonize the ionizer pulse with the pulse of discharge and facilitates accumulation of negative ions useful for discharge stabilization (increase of volume discharge time and, consequently, the value of energy deposited in the volume discharge). The negative ions and electrons are continuously present in the reactor plasma in the maximum possible (for the given ionization rate) concentration.

As in the case of DNP, the lasers with CNP can be subdivided in accordance with the traditional division of all gas lasers into molecular, atomic, and excimer lasers. Lack of information about lasing on transitions of metal vapor ions for CNP is primarily due to technical difficulties in maintaining the required temperature control of the active medium and, correspondingly, optimal concentration of the metal vapor.

There are other proposals for a CNP. In particular, Prelas and co-workers suggested using a nuclear pumped source of UV radiation for pumping of active laser media. However, there is no information about lasing with this way of CNP (Andriyahin *et al.*, 1969).

CNP Lasers on Vibrational Transitions of CO_2 and CO Molecules

Utilization of pulsed nuclear reactor for lasers active media ionization was first proposed in 1969 (Andriyahin *et al.*, 1969). Doubling of CO_2 laser output power was achieved by the proton beams used for laser active medium ionization, simulating the products of the He^3(n,p)T nuclear reaction (Andriyahin *et al.*, 1972; 1973). The use of the products of the B^{10}(n,α)T nuclear reaction for ionization of the CO_2 laser active medium was demonstrated by Professor George Miley of the University of Illinois and his co-workers (Gauley *et al.*, 1971).

The development of the electron beam-controlled laser pumping electric-ionization method (Basov, 1971; Danilyzhev *et al.*, 1976) inspired its implementation in the radiation field of stationary nuclear reactors. The principle of the electric-ionization method of excitation can be presented as follows. Compressed gas is placed between two electrodes under a voltage. Ionizing radiation through the gas creates conductivity and generates an electric current. The concentration of free electrons in this case depends only on the intensity of ionizing radiation and is independent of the applied electric field strength.

That is, unlike the gas-discharge laser where the electrons are not only involved in gas conductivity, but also create conductivity itself by direct ionization, these functions are separated in electric ionization lasers. Free electrons are generated by the external ionizer, and the value of the current increases with electric field intensity, increasing only due to an increase of the electron drift velocity. This helps us to eliminate some significant deficiencies occurring in gas-discharge lasers. First, the electric-ionization method removes restrictions for working gas pressure and the size of the system. This circumstance is an essential feature of the electric-ionization method of energy introduction in the laser active medium, fundamentally distinguishing it from other methods of combined pumping. Second, it becomes possible to achieve the ultimate efficiency of the laser using the electric-ionization method of pumping. In the self-sustained discharge, the operating value of the reduced field strength E/P is determined by the condition of the self-sustaining discharge, and it is significantly higher than the optimum one for the excitation of molecule vibrational levels. Using the electric ionization method of excitation, it is possible to consider the E/P value optimum when the energy released in the gas is converted into the energy of molecules vibration with an efficiency rate close to 100%, since the conductivity is formed by ionizing radiation. Third, the electric-ionization method provides a high level of specific power of the discharge.

Despite the encouraging results obtained in the studies of electric-ionization lasers with different sources of external ionization, the issue of feasibility of this pumping method in the conditions of the stationary nuclear reactor remained to be addressed.

For this purpose, the INP NNC RK and the Lebedev Physical Institute of the Academy of Sciences (PIAS) of the USSR conducted comprehensive studies of nuclear-excited plasma in the active zone of the stationary nuclear reactor (Batyrbekov *et al.*, 1979*a*, 1983). In particular, the probe diagnostics of plasma in a CO_2:N_2:He^3 = 1:4:5 gas mixture at 10 atm pressure showed that electron concentration in the mixture is equal to $2 \times 10^{12}/Cm^3$ at 2×10^{14} n/Cm^2s thermal neutrons flux (Batyrbekov *et al.*, 1978*b*). The achieved ionization rate provided the input of power at the level of ~0.5 kW/cm^3 and evidence for the possibility of the electric-ionization method of pumping.

Generation with the electric-ionization pumping method was obtained for the first time in 1976 (Batyrbekov *et al.*, 1977*a*; 1977*b*; 1977*c*). The generation was produced on the vibrational transitions of a CO_2 molecule with ionization of a CO_2:N_2:He = 1:4:5 laser mixture by the products of He^3(n,p)T nuclear reactions in the active zone of the stationary WWR-K nuclear reactor.

The same research group conducted the study of CO-N_2-He^3-induced plasma in the active zone of the stationary nuclear reactor (Batyrbekov *et al.*, 1979*a*; 1983) and obtained the pulse-periodic and stationary generations on the vibrational transitions of the CO molecule in 1978 (Batyrbekov *et al.*, 1978*b*).

The output characteristics of the electric-ionization lasers with ionization of active media by the products of He3(n,p)T nuclear reactions on the vibrational transitions of CO_2 (Batyrbekov *et al.*, 1978*a*; 1978*b*; 1983) and CO (Batyrbekov *et al.*, 1978*b*; 1982*a*; 1983) molecules are shown in Table 1.

CNP Excimer Lasers

Excimer molecules are those molecules existing only in the excited state. The main state of such molecules is either dissociable or has a very small well on the curve of the potential energy. Thus, the lower state of excimer molecules is practically unpopulated, and an inverse population is determined only by the population of the upper laser level (Rhodes, 1979). The interest in these molecules is caused by the possibility to obtain powerful radiation in the VUV, UV and visible spectral regions and high quantum yields up to 50% (luminescence of Xe_2^* excimer molecules).

Table 1. *Output characteristics of CO_2 and CO CNP lasers*

Active laser medium	Output energy (J)	Efficiency (%)	Specific output energy (J/l amagat)
CO_2	5.2	6.4	11
CO	10	12	18

Excimer lasers emit in the range from Ar_2^* molecules radiation with a wavelength of $\lambda = (127 \pm 4)$ nm to ZnI with $\lambda = (600 \pm 4)$ nm. The essential properties of the excimer lasers include: high efficiency (1–10%), high specific energy (up to 40 J/l per pulse), and the possibility, due to a wide radiation band, of smooth laser frequency tuning in the range of 10–100 nm. These advantages of excimer lasers offer the possibility of their use in communication and location, isotope separation and medicine, laser thermonuclear synthesis and nonlinear optics.

On the other hand, the short wavelength and very short lifetime of excimer molecules (~10 ns) necessitate a high density of the excimer molecules for lasing, that is, the need for a considerable amount of energy in a very short time. This is due to the fact that the amplification factor of the laser is proportional to the square of the laser wavelength and is inversely proportional to the line width of spontaneous transition.

The relatively flat rise front and the long duration of pumping neutrons pulses make practical application of the pulsed reactors impossible for the pumping of excimer lasers with emission in the UV spectrum. However, we should note the unsuccessful attempts made by some researchers to reach excimer laser radiation (XeF*) with DNP (Body *et al.*, 1978; Hohl, 1978).

Also, it was proposed in Aleksandrov *et al.* (1981) to use the effect of negative ions accumulation in plasma of excimer lasers working media to reduce the external ionizer power. Such a reduction of the ionizer power to a level typical of continuous sources of ionizing radiation (stationary nuclear reactors, continuous electron beams, radionuclides, etc.) is necessary for lasers with high pulse repetition frequency.

The first excimer lasing in the steady state nuclear reactor was achieved in the INP NNC RK together with scientists from FIAS (Basov *et al.*, 1981; Batyrbekov *et al.*, 1982*b*; Batyrbekov, 1994).

Lasing was achieved at the transition of the XeF* molecule in the 3He-Xe-NF3 mixture. It should be noted that high specific characteristics were not achieved in these experiments due to the influence of neutrons and gamma radiation on elements of laser installation, such as a resonator, capacitors, etc.

The first reactor experiments were done with the ^{3}He:Xe:NF_3 = 300:1.5:1 mixture at a pressure of 0.9 atm. Under these conditions, the maximum power density of discharge energy put into the gas is ~50 J/l. Figure 8 shows the dependence of the threshold of charging voltage on the battery of reservoir capacitors from thermal neutrons flux.

The results obtained confirmed the conclusion that the excimer laser with CNP can operate at low temperatures (~10^{12} n/Cm^2s) of thermal neutrons flux. Thus, the ability to produce an excimer laser with a working volume of tens

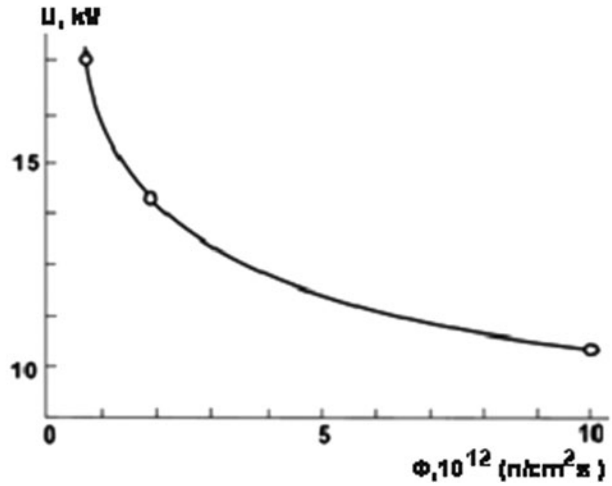

Fig. 8. Dependence of the intensity threshold value on the flux of thermal neutrons.

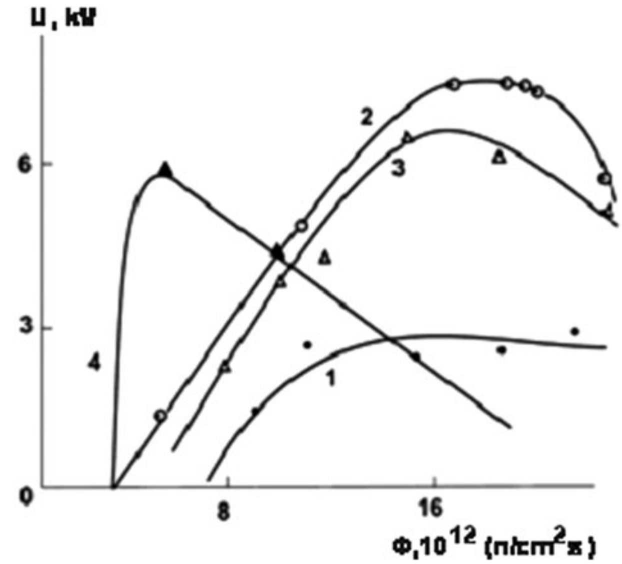

Fig. 9. Dependence of laser radiation output energy (**1–3**) and efficiency (**4**) of the laser on the voltage value on reservoir capacitors for various flows of thermal neutrons Φ_t (n/Cm^{2}s): 1, 10^{11}; 2 and 4, 10^{12}; 3, 10^{13}.

of liters and a pulse repetition frequency up to 10 kHz was demonstrated.

CNP Infrared Laser at Xenon Atomic Transitions

The interest in CNP lasers on the transitions of xenon atom is primarily due to the record output characteristics of DNP lasers obtained today on xenon atomic transitions.

The first laser with a CNP on atomic transitions of xenon was produced in the INP NNC RK (Batyrbekov *et al.*, 1989*a*) at the WWR-K nuclear reactor.

The experiments were performed in three laser units (LU). Each of the three tested LU had its own design features defined by its function in the experiment. Aggravating capacitors were not used in LU No. 2 and No. 3, which allowed working with large (up to 10^{14} n/Cm^{2}s) neutron fluxes and high temperatures. In LU No. 1 and No. 3, a gas mixture was ionized by the products of ^{3}He(n,p)T + 0.76 MeV nuclear reaction. In LU No. 2, experiments were performed with no-helium gas media, so the fission products of ^{235}U(n,f)FF were used for active medium ionization. A uniform layer of U-235 oxide was deposited on additional electrodes with ~10 mg/Cm^2 density. The temperature of the laser medium in LU No. 3 was controlled by varying the ^{4}He pressure between the two casings: the external casing was cooled by reactor water, and the internal side was radiation heated. The temperature was measured with a chromel-alumel thermocouple, which was caulked in the bottom of the inner LU casing and taken out to the reactor cover through a 10 mm diameter pipe, which was also used for helium supply and pumping.

Figure 9 shows the dependence of the output laser energy E (LU No.1) on the voltage *U* on reservoir capacitors at various Φ_t thermal neutron fluxes. The minimum value of thermal neutrons flux is $\Phi_t = 10^{11}$ n/Cm^{2}s for laser operation. The decrease of laser output parameters (~15%) observed in the Figure with an increase of Φ_t from 10^{12} to 10^{13} n/Cm^{2}s is associated with deterioration of LU parameters (in particular, capacitors) as a result of radioactive heating in the active zone of the nuclear reactor (Batyrbekov, 2008*e*).

Figure 10 shows the results of laser tests on an Ar:Xe = 100:1 mixture at 2 atm total pressure with ionization by the products of U^{235}(n,p)T nuclear reaction (LU No. 2). The maximum values of specific energy have been achieved at 20 kV charging voltage and 10^{14} n/Cm^{2}s thermal neutrons flux. The use of an active mixture on He and a longer pumping time made it possible to increase the laser output parameters for 1.5 orders of magnitude.

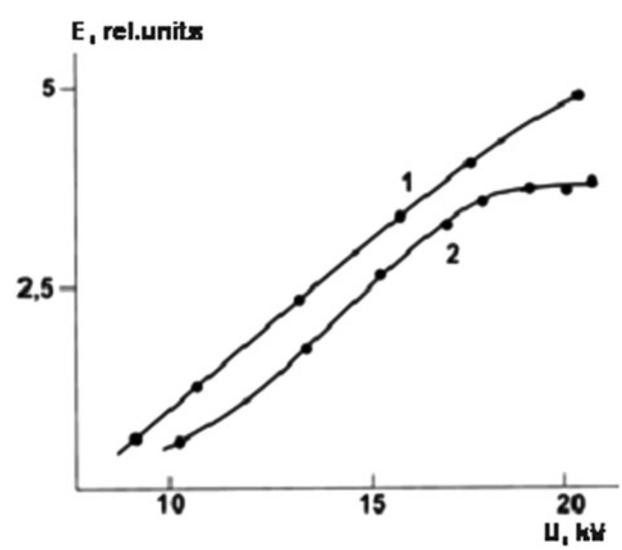

Fig. 10. Energy of laser radiation as a function of charging voltage at $\Phi_t = 3 \times 10^{13}$ (**1**) and 10^{14} (**2**) n/Cm^{2}s.

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The same paper reported on studies of laser operation at high temperatures of the active medium. It was established that increasing the temperature of the active medium up to 650°C within the measurement error did not affect the laser output parameters.

The CNP laser on atomic XeI transitions, unlike the previously studied CO, CO_2, and CNP excimer lasers, employs as an active medium a mixture of inert gases only; that is, the problem of active medium degradation does not exist. Lasing was produced on high electronic transitions allowing operation at high temperatures (>650°C) of the active medium (Batyrbekov, 2008*f*; 2008*g*).

Lasers with Radioisotope Ionization

The first attempt to create a non-self-sustained electrical discharge laser was made in 1978 (Bigio, 1978), but the use of low-activity Am^{245} sources, located on one side of the electrode, did not allow lasing at gas pressures above 0.5 atm. The creation of a pulsed CO_2 laser with active medium ionization by plutonium α-radiation was also reported previously (Lavrenuyk *et al.*, 1983; Glushchenko & Lavrenyuk, 1986).

Lasing on Xe and Ne atomic transitions with active medium ionization by α-particles was first achieved in the INP NNC RK (Batyrbekov *et al.*, 1987*e*; 1989*b*). The scheme with transverse excitation with discharge of low inductance capacity through the ionized gap was used in the laser. Twenty sources of PT^{210} were used as the ionization sources, with 3×10^{10} Bq total activity. For the mixture of He(1.5 Atm)-Ar(0.5 Atm), the ionization rate was $2 \times 10^{12}/Cm^3/s$, and the electron density was $n_e \sim 2 \times 10^9/cm^3$. The unit allowed using UV radiation for ionization purposes.

Lasing was produced on the XeI 5d-6p transition in the He-Ar-Xe mixture (>40% of the energy was for $\lambda = 1.73\ \mu m$). The results of the mixture optimization are shown in Figure 11. The mechanical strength of the chamber did not make it possible to obtain the maximum output parameters of the laser at pressure rates above 2 atm.

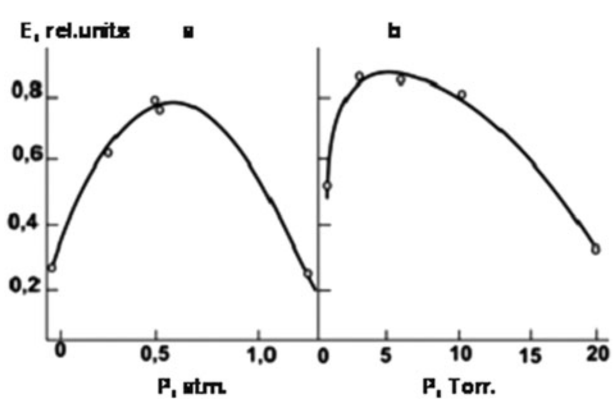

Fig. 11. Dependence of laser radiation energy on argon partial pressure in the He–Ar–Xe (5 TTrr) mixture (full pressure of the mixture is 1.8 atm (**a**) and xenon partial pressure in the mixture He(1.3 atm)–Ar(0.5 atm)–Xe (**b**).

Lasing with $\lambda = 595.2$ nm on the $3p'[1/2]_0$-$3s'[1/2]_1$ NeI transition was produced only in the mixture with neon and hydrogen (Batyrbekov *et al.*, 1989*b*). The influence of additives H_2, Ar, D_2 on the output energy of laser radiation is shown in Figures 12 and 13. The need for the presence of hydrogen in neon mixtures with argon (which, like H_2, is selectively involved in emptying the lower laser level) in addition to cooling of the electrons involved in dissociative recombination of molecular ions is explained by the influence of H_2 on the degree of vibrational excitation of Ne_2^+ molecular ions,

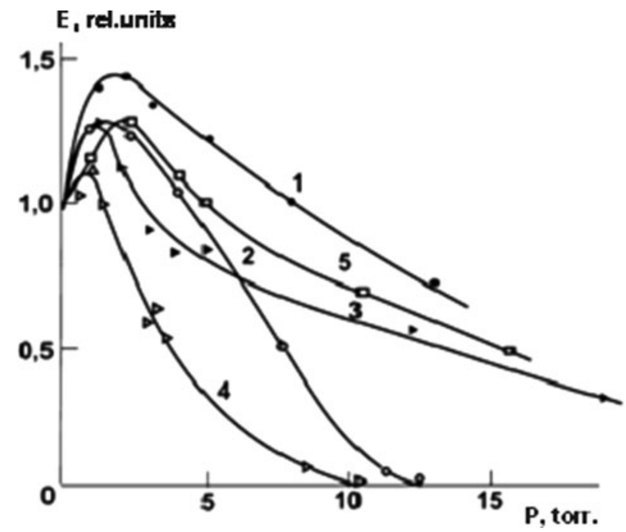

Fig. 12. Dependence of laser radiation energy with λ = 585.2 nm on the additives Ar (**1,2**), D2 (**3,4**), and H2 (**5**) to the mixtures 190 Torr He+ [75 Torr Ne + 15 Torr (H_2 + Ar) (1), 15 Torr (H_2 + D_2) (3), 15 Torr H_2 (2,4,5)].

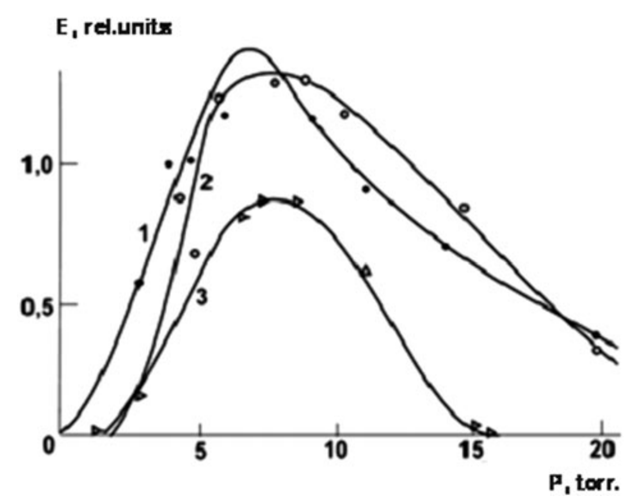

Fig. 13. Dependence of laser radiation energy with λ = 585.2 nm on additives H_2, 1; D_2, 3; and Ar, 2 in the mixture of He:Ne:H_2 = 190:75:10 Torr.

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Table 2. *Calculations for the gaseous β-emitters Kr^{85} and Ar^{42} used for volume ionization of laser active media*

Mixture	Laser	λ, μm	P, atm	S, $cm^{-3}s^{-1}$	n_e, cm^{-3}	n_n, cm^{-3}
$Ne:Kr^{85}:F_2 = 85:15:0.02$	KrF*	0.248	10	8.4×10^{14}	2.5×10^{6}	2.5×10^{10}
$He:Ar^{42}:Xe = 100:50:1$	Xe I	~2	10	4.7×10^{14}	3×10^{10}	–
$He:Ne:Ar^{42}:H_2 = 220:30:7:10$	NeI	0.585	0.5	10^{10}	10^{10}	–
$CO:Ar^{42} = 1:9$	CO	~5	1	1.2×10^{10}	3×10^{10}	–
$CO:Kr^{85} = 1:9$	CO	~5	1	5×10^{14}	6×10^{10}	–

which affects the population of the $3p'[1/2]_0$ (Kopai-Gora *et al.*, 1990; Sinyanskiy, 1995) state.

These experiments with radioisotope ionization failed to obtain lasing on transitions of excimer molecules, although using UV ionization helped in obtaining lasing on XeF and XeCl transitions. This is due to an insufficient degree of ionization of the working medium.

The experiments performed with the excimer lasers with ionization by radiation of the stationary nuclear reactor showed that the minimum required value of thermal neutrons flux is 10^{12} n/Cm^2s, which corresponds to the density of negative ions $n_n \approx 10^{10}/Cm^3$ (Batyrbekov, 1994). In order to produce such a degree of ionization, it is necessary to have Po^{210} of $\sim 10^{10}$ Bq/Cm^2 specific activity.

Table 2 presents the calculated *S* ionization rates and concentrations of electrons and negative ions n_e and n_n during the use of gaseous β-emitters, Kr^{85} and Ar^{42}, for volume ionization of electric discharge lasers active media. Some advantages of the proposed continuous volume source of laser mixtures ionization are the following:

(1) a high homogeneity of gas ionization, even higher than in the case of using nuclear reactions of the He^3(n,p)T or U^{235}(n,f)F type;
(2) no restrictions on system size and gas pressure, because the larger they are, the higher the ionization homogeneity;
(3) the maximum efficiency (~60%) for electric discharge lasers was obtained for CO-Ar (Mann, 1976).

CONCLUSION

Current progress in the field of direct conversion of the energy of nuclear reactions into the energy of laser radiation indicates the possibility of nuclear-excited high-power laser systems with 0.3–1 MJ per pulse and 0.25–0.3 Hz pulse repetition rate (Batyrbekov, 2008*a*). Further improvement of the characteristics of the nuclear-optical converter is primarily dependent on the achievement of corresponding efficiency of nuclear energy conversion into laser radiation, that is, it implies a further search and study of highly productive active media for nuclear-excited sources of non-equilibrium optical radiation – direct nuclear pumped lasers. An obvious way to increase the efficiency of such a transformation is by the reduction of the wavelength and the potential of buffer gas ionization.

The kinetics study of the main plasma-chemical processes occurring in nuclear-excited laser plasma is of equal importance. The most promising, in terms of nuclear energy conversion efficiency, are the atomic recombination lasers on allowed bound–bound electronic transitions; this is primarily determined by the low temperature involved in recombination of molecular ions, secondary electrons in nuclear-induced plasma and large sections of stimulated transitions.

However, the above-mentioned shortcomings in systems with direct conversion of nuclear energy into laser radiation encourage further parallel investigations of lasers with CNP; the presence of active media capable of working in the conditions of both DNP and CNP also remains very important.

Traditionally, the study of lasers with DNP and CNP was performed independently by different research groups. Therefore, the concept developed in Kazakhstan for studies of the active media for lasers capable of working both with DNP and CNP is of interest. This approach allows utilizing the advantages and eliminating the disadvantages of both the nuclear pumping methods. The need for the simultaneous use of either DNP or CNP is determined by their various practical applications.

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