ABSTRACT

of the dissertation for the degree of Doctor of Philosophy (PhD) in the educational program 8D05301 – «Physics»

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Experimental investigation of the processes of conversion of the energy of products of $^{6}Li(n,\alpha)^{3}H$ nuclear reaction into the energy of an optical radiation

General overview of the work. The dissertation work is devoted to the experimental study of the processes of conversion of the kinetic energy of the products of the nuclear reaction $^{6}Li(n,\alpha)^{3}H$ into the energy of optical radiation. The main regularities of the formation of radiative states in low-temperature nuclear-excited plasma of noble gases under excitation by products of the given nuclear reaction have been established.

Relevance of the research topic. The study of optical (laser and spontaneous) radiation of nuclear-excited plasma is of interest for the development of a method of energy output from a nuclear reactor, as well as for the control and regulation of nuclear reactor parameters. Direct pumping of active media is usually realized by products of nuclear reactions with thermal neutrons of a nuclear reactor: $^{3}He(n,p)^{3}H$, $^{10}B(n,\alpha)^{7}Li$, $^{235}U(n,f)F$, or others. The working medium must contain ^{235}U, ^{3}He, or ^{10}B, or a compound with these isotopes is applied to the chamber walls. The use of nuclear reaction with lithium-6 with thermal neutrons has been less investigated. The relatively long path length of tritium nuclei in lithium (130 μm) and gas media (~35 cm in helium at atmospheric pressure) makes it possible to excite significant volumes of gases and provide a large value of the power inserted into the gas compared to reaction products with ^{10}B. Significant interest in studies in this area is also related to the essential difference between the mechanisms of energy level population at pumping and the population processes in gas-discharge lasers.

In this dissertation work, to study the regularities of formation of radiative states in noble gases under excitation by products of the nuclear reaction $^{6}Li(n,\alpha)^{3}H$, the processes of lithium sputtering, interaction of its vapors with the buffer gas, and the parameters determining the possibility of creating population inversion at the 2p-1s -transition are considered. The relevance of the thesis work is conditioned by the solution of the scientific and technical problem of conversion of nuclear reaction energy into optical radiation energy and the necessity to reveal the regularities of formation of radiative states in nuclear-excited plasma based on noble gases at pumping by $^{6}Li(n,\alpha)^{3}H$ reaction products. It is necessary to establish whether a sufficient density of lithium vapor in the gas will be achieved to effectively disperse the 1s-level of the noble gas atom and to create a population inversion at the 2p-1s -transition. The solution of this problem requires a comprehensive approach, including the study of noble gas luminescence and lithium sputtering processes under excitation by a nanosecond electron beam, as well as reactor experiments on a pulsed nuclear reactor IGR with a thermal neutron flux of $7 \cdot 10^{16}$ n/cm^{2}s at a pulse duration of 0.12 s.

To realize this goal, it is necessary to develop a special experimental setup, an irradiation device with a lithium source of excitation of gas mixtures, and a methodology for in-pile experiments at the IGR reactor. Preliminary studies are performed on a nanosecond electron accelerator, which makes it possible to study the processes of lithium sputtering into noble gases under the action of an electron beam under more convenient conditions, to determine the differences in comparison with excitation by nuclear particles, and thus significantly reduce the volume of necessary reactor experiments.

Thus, the subject of the dissertation work is conditioned and justified by the necessity of a fundamental study of processes in nuclear-excited plasma of gas mixtures. The work is aimed at obtaining new experimental data on lithium sputtering into noble gas under excitation by electron beam and products of the $^6Li(n,\alpha)^3H$ nuclear reaction. Implementation of the set tasks requires comprehensive research using both acceleration and reactor facilities, which allows full use of the scientific and technical potential of the National Nuclear Center of the Republic of Kazakhstan.

The purpose of this dissertation– to establish the main regularities of the formation of radiative states in noble gas mixtures during lithium sputtering by products of the $^6Li(n,\alpha)^3H$ nuclear reaction.

In order to achieve the set goal, the following **tasks** should be solved:

1) to develop and manufacture an experimental setup and irradiation device with a lithium source of excitation of gas media for conducting studies at the pulsed nuclear reactor IGR;
2) to develop a methodology for in-pile experiments to study spectral and temporal characteristics of optical radiation of gas mixtures excited by the products of the $^6Li(n,\alpha)^3H$ nuclear reaction;
3) to obtain reproducible experimental data on spectral-temporal characteristics of optical radiation of gas media, to determine the main plasma-chemical reactions, as well as to identify the mechanisms of population and deactivation of energy levels at 2p-1s -transitions of noble gas atoms upon excitation by $^6Li(n,\alpha)^3H$ nuclear reaction products.

The object of the study is low-temperature nuclear-excited plasma of gas media formed by the interaction of $^6Li(n,\alpha)^3H$ nuclear reaction products with noble gas mixtures (He-Ar, He-Xe) under irradiation conditions in the core of an IGR pulsed reactor.

The subject of the study is the kinetics of the processes of population and deactivation of energy levels at 2p-1s -transitions of noble gas atoms under excitation by the products of the $^6Li(n,\alpha)^3H$ nuclear reaction.

Research Methods. In the dissertation work, spectral, mass spectrometric and computational-theoretical methods were used to realize experimental studies.

The study of spectral-temporal characteristics of radiation of gas mixtures (He-Ar, He-Xe) at their excitation by ionizing radiation was conducted using the spectral method of plasma diagnostics. This method, in combination with the measurement of the time dependence of the pulsed reactor power, allowed to determine the generation threshold, shape and duration of optical radiation pulses.

The spectra were recorded using an optical spectrometer QE Pro-Abs by Ocean Insight, operating in the wavelength range from 200 to 950 nm, with licensed software OceanView. A line of Thorlabs photodiodes with different spectral sensitivities, as well as a MDR-204 monochromator with a PDM02-9113W-CN FES module were used to record signals with high temporal accuracy. The time characteristics of the signals were recorded using a Tektronix TBS2204B digital oscilloscope with licensed software. Mass spectrometry was carried out using an RGA-100 instrument to control the qualitative composition of gas mixtures.

Additionally, numerical modeling methods were applied - thermophysical and neutron-physical calculations, licensed software packages such as: ANSYS FLUENT and MCNP5, aimed at substantiating the parameters of irradiation devices, as well as at ensuring the safety of experiments in the core of the pulsed reactor IGR.

Also, a compact nanosecond electron accelerator, based on the Arina-2 X-ray defectoscope, was used in this work, which made it possible to preliminarily study the processes of lithium sputtering into noble gas under more controlled conditions outside the reactor core.

The scientific novelty of the work consists in the first time:

– an experimental setup and irradiation device with a lithium source of excitation of gas mixtures for in-pile studies at the IGR reactor have been developed and manufactured. The developed device is protected by a utility model patent “Irradiation device for conducting experiments on pulsed graphite reactor” (No. 7162, published on 03.06.2022).

– methodology for conducting reactor experiments in the core of the IGR reactor to study spectral and temporal characteristics of optical radiation of gas mixtures excited by products of the 6Li(n,α)3H nuclear reaction was proposed and tested;

– new experimental data on spectral-time characteristics of radiation of gas mixtures (He-Ar, He-Xe) excited by 6Li(n,α)3H nuclear reaction products under reactor irradiation conditions were obtained;

– mechanisms of formation and deactivation of radiative states at 2p-1s -transitions in noble gas mixtures at pumping by 6Li(n,α)3H nuclear reaction products were revealed and established.

Key provisions for defense:

1. Developed experimental setup, irradiation device with a lithium source for excitation of gas mixtures, and methodology for in-pile experiments at the pulsed IGR reactor.

For the first time, a specialized experimental setup designed to study the spectral and temporal characteristics of optical radiation arising from the excitation of gas mixtures by the products of the $^{6}Li(n,\alpha)^{3}H$ nuclear reaction was created. The experimental setup includes a gas-vacuum system, an information-measuring system (IMS), and an irradiation device (ID) with a lithium source of excitation of gas media, placed directly in the central experimental channel of the IGR reactor - in the area of maximum thermal neutron flux. The gas-vacuum part is realized on the basis of TURBOLAB 90i 63ISO-K/SC7plus/F/N post to create and provide the necessary conditions in the ID. The IIS includes three subsystems: control and stabilization of the temperature of the ID casing; optical registration system; and mass-spectrometric diagnostics of the gas phase. For registration of spectral-temporal characteristics of optical radiation of gas mixtures, QE Pro-Abs spectrometer (Ocean Insight, Singapore) with OceanView licensed software is used, silicon DET100/AM and indi-gallium PDA10D2 photodetectors (Thorlabs, USA), oscilloscopes TBS2204B (Tektronix) with licensed software Keithley KickStart Software and TPS2012 (Tektronix), photomultiplier tube module PDM02-9113-CN (ET Enterprises, UK), coupled with the MDR-204 monochromator (LOMO PHOTONIKA plus, RF), which provides high-precision measurement of optical radiation parameters. The methodology of reactor experiments in the “Burst” mode was developed and tested in the form of a regulated Program. The technique includes step-by-step procedures for preparation, start-up, synchronization with the reactor pulse, and processing of the obtained data, ensuring reproducibility and safety of the research.

2. Spectral and temporal characteristics of optical radiation during lithium sputtering into noble gas under the influence of ionizing radiation.

In order to simulate the processes of excitation of the gas medium by products of the $^{6}Li(n,\alpha)^{3}H$ nuclear reaction, a series of experiments with irradiation of the lithium layer by a beam of fast electrons with an energy of 150 keV and a duration of 5 ns was performed. The irradiation chamber was filled with argon, krypton or xenon at pressures ranging from 10 to 60 kPa. At the temperature of the lithium layer 650-680 K, lithium lines appear in the emission spectrum, the intensity of which increases significantly with increasing temperature. Light emission at the lithium atom transitions appears simultaneously with emission at the transitions of noble gas atoms and reaches a maximum in 20-30 ns after the electron beam pulse.

A series of in-pile experiments on the pulsed IGR reactor was conducted, during which new experimental data were obtained and repeatable spectral and temporal characteristics of optical emission of gas mixtures excited by the products of the $^{6}Li(n,\alpha)^{3}H$ nuclear reaction were recorded. A mixture of He-Ar and He-Xe at pressures of 100 kPa and 99.4 kPa, respectively, in a 100:1 ratio was used as the gas mixtures examined. The thermal power of the IGR reactor in these experiments was 8.9 GW and 9.49 GW in the "Burst" reactor mode of operation, respectively. Emission spectra as well as emission oscillograms tuned to wavelengths of 750.4 nm for the He-Ar mixture and 823 nm for the He-Xe mixture were recorded, respectively.

3. Kinetics of plasma processes and mechanisms of population and deactivation of energy levels at 2p-1s -transitions of noble gas atoms under excitation by $^{6}Li(n,\alpha)^{3}H$ nuclear reaction products.

Based on the results of out-of-pile experiments, it has been established that the main channel for populating lithium levels for a time comparable to the duration of electron beam excitation is surface ionization due to the interaction of the lithium layer with ions and metastable atoms of noble gas. Subsequently, light emission is produced by plasma chemical reactions in the gas volume. At layer temperatures corresponding to saturated lithium vapor pressure from 1 mPa to 130 mPa, the necessary vapor density (≥ 1 Pa) is provided mainly by lithium sputtering by nuclear particles.

On the basis of reactor experiments, the main plasma-chemical reactions are determined and the rates of processes occurring in the nuclear-excited plasma of He-Ar and He-Xe gas mixtures under excitation by the products of the $^6Li(n,\alpha)^3H$ nuclear reaction are calculated. Based on the results of reactor experiments, the mechanisms of population and deactivation of energy levels at 2p-1s -transitions of noble gas atoms have been established, and the kinetics of plasma processes have been analyzed.
The main channel leading to the population of lithium levels is the Penning process (R - noble gas atom):

$$R^*(1s) + Li \rightarrow R + Li^+ + e,$$

Excitation of sputtered lithium atoms occurs as a result of further plasma chemical reactions in the gas. Lithium can selectively quench the lower level at 2p-1s - transitions of noble gases.
Comparison of the results of reactor and out-of-pile experiments allowed the general regularities of plasma processes under different types of ionizing effects.

Practical significance. The experimental data obtained in the dissertation work and the revealed regularities of the kinetics of the processes of population and deactivation of energy levels in noble gases under excitation by the products of the $^6Li(n,\alpha)^3H$ nuclear reaction are of practical value for the development of new approaches to the output of energy from a nuclear reactor in the form of optical radiation. The results can be used in the development of nuclear power plants capable of generating coherent (laser) or spontaneous optical radiation. The research is also of interest from the point of view of creation of ionizing radiation detectors, as well as in systems of control and diagnostics of nuclear reactor core parameters. The act of implementation of the results of the thesis work in the procedure of conducting applied scientific research in the field of direct conversion of kinetic energy of nuclear particles into optical radiation energy in the branch of IAE NNC RK was received.

The obtained results of experimental research were also included in the Proceedings of the NNC RK “Research in support of the development of nuclear energy in the Republic of Kazakhstan” / under the general editorship of E.G. Batyrbekov, and V.V. Baklanov, Branch IAE RSE NNC RK Ministry of Energy of RK.- Kurchatov, 2021.- 278 p.: il.269. - ISBN 978-601-06-7963-4".

Author's contribution. The formulation of the goal and objectives of the dissertation research, the discussion of the obtained results, and the formulation of the main conclusions were carried out in close collaboration with scientific advisors. The author's contribution consists of conducting an analytical review of the literature and patent search, actively participating in the development of methodological approaches to ensuring the implementation of out-of-pile studies and experiments on the IGR and IVG.1M reactors, preparing and conducting the experimental work, analyzing and processing the obtained experimental data, performing calculation work, studying the regularities of the formation of emitting states in mixtures of noble gases when lithium is pumped by the products of the nuclear reaction

$^{6}Li(n,\alpha)^{3}H$, as well as preparing the main publications on the topic of the dissertation. All work was carried out in close cooperation with leading scientists and specialists from the Branch of the Institute of Atomic Energy of the National Nuclear Center of Kazakhstan (IAE NNC RK).

The connection of the dissertation topic with the plans of research programs. A significant part of this work was carried out with financial support from the State Institution "Committee of Science of the Ministry of Education and Science of the Republic of Kazakhstan" under Contract No. 187 dated November 16, 2020, on the topic "Study on the creation of quasi-continuous on p-s transition laser of noble gas atom with excitation by products of $^{6}Li(n,\alpha)^{3}H$ nuclear reaction" (AP08856017). Additionally, part of the work was carried out within the framework of the implementation of the scientific and technical program "Development of Nuclear Energy in the Republic of Kazakhstan" (BR09158470) on the topic: "Development of the physical principles for energy conversion from a nuclear reactor in the form of coherent optical radiation."

The degree of validity and reliability of the results obtained in the work is ensured by the correctness, accuracy, and originality of the tasks set, mutually consistent results of reactor and non-reactor experiments, mass spectroscopy, and optical emission spectrometry. The main results of the thesis have been published in peer-reviewed foreign scientific journals included in the Scopus and Web of Science databases.

Approval and Presentation of Research Results. The main results of the dissertation were presented and discussed at 10 international conferences:

1. International online conference «Advanced manufacturing materials and research: new technologies and techniques AMM&R2021» (Ust-kamenogorsk, Kazakhstan, 2021, February 19);
2. IX International Conference "Semipalatinsk Test Site: Legacy and Prospects for the Development of Scientific and Technical Potential" (Kurchatov, Kazakhstan, September 7–9, 2021);
3. XV International conference on pulsed lasers and laser applications. – AMPL-2021 – Tomsk, October 12-17, 2021.;
4. 20th International Conference Laser Optics (ICLO 2022).– St.Petersburg, Russian Federation, June 20-24, 2022;
5. 10th International Conference on Nanomaterials and advanced energy storage systems (INESS-2022), (Astana, August 4–6, 2022);
6. 13th International Conference on Tritium Science and Technology - Tritium 2022. – Bucharest, Romania, October 16-21, 2022;
7. 8th International Congress on Energy Fluxes and Radiation Effects (EFRE 2022). – Tomsk, Russia, October 2-8, 2022;
8. VIII International Conference "Laser and Plasma Research and Technologies" (LAPLAZ-2022), dedicated to the 100th anniversary of Nobel Laureate in Physics Nikolay Gennadiyevich Basov (Moscow, NRNU MEPhI, Russian Federation, March 22–25, 2022);
9. XXIII International Symposium on Solid State Dosimetry – ISSSD-2023 – Monteria, Colombia. September 25-29, 2023;

X International Conference "Semipalatinsk Test Site: Legacy and Prospects for the Development of Scientific and Technical Potential" (Kurchatov, Kazakhstan, September 12–14, 2023)

At R&D Conference-Competition of Young Scientists and Specialists of the RSE "National Nuclear Center of the Republic of Kazakhstan":

1. XX R&D Conference-Competition of Young Scientists and Specialists of the RSE NNC RK, Institute of Atomic Energy, NNC RK (Kurchatov, Kazakhstan, October 6–8, 2021);

1. Third Annual Meeting of the Kazakhstan Physical Society (Kurchatov, Kazakhstan, June 7–11, 2023).

In addition, the main results of the dissertation were presented and discussed at academic seminars of the Department of Physics, at joint academic seminars of the Faculty of Natural Sciences and Technologies, at the Scientific and Technical Council of Sarsen Amanzholov East Kazakhstan University, as well as at the Scientific and Technical Councils of the RSE NNC RK and its Institute of Atomic Energy Branch, and at PhD student seminars.

Publications. The main results of the dissertation are published in 20 printed works, including: 5 articles in journals indexed in the Scopus and Web of Science databases, 1 utility model patent of the Republic of Kazakhstan, 14 papers in the proceedings of international conferences, and 1 in other publications.

The structure and scope of the dissertation. The dissertation consists of an introduction, five chapters, a conclusion, and a list of references. The work is presented on 112 pages and includes 52 figures, 10 tables, and a reference list comprising 102 sources.