Abstract

to the dissertation work submitted for the degree of Doctor of Philosophy (Ph.D) in the specialty «6D060500 – Nuclear physics»

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THE PARAMETERS OF THE NEUTRON YIELD AND EROSION OF MATERIALS IN THE INSTALLATIONS OF «PLASMA FOCUS»

General description of work

The dissertation investigates the emission parameters of neutrons produced in DD nuclear fusion reactions in a plasma focus device, as well as the mechanisms influencing their generation. In addition, radiation erosion and damage resulting from nuclear interactions of neutrons and ions with tungsten (^{182}W) and molybdenum (^{92}Mo) plates are studied.

Relevance of the topic

At present, the problem of achieving controlled thermonuclear fusion is one of the fundamental directions of Nuclear Physics. Research in this field is closely related not only to energy applications, but also to the kinetics of high-energy nuclear reactions, fusion products, neutron generation mechanisms, and the specific features of their interaction with matter. In recent years, particular interest has been growing in pulsed plasma devices that allow direct control of particle energy for conducting such studies. One of these systems is the plasma focus (PF) device. It enables the formation, within a short time (~10-50 ns), of plasma with densities on the order of ~10^{19}-10^{24} cm^{-3} and ions with energies sufficient to initiate fusion reactions. As a result of DD fusion reactions occurring in plasma focus devices, neutrons with energies of 2.45 MeV, high-energy ion fluxes, and intense X-ray radiation are generated. Such neutron fluxes serve as an important experimental tool for studying the kinetics of nuclear reactions, identifying fusion mechanisms, and analyzing the effects of nuclear radiation on materials. However, the problem of improving the stability and efficiency of neutron emission in PF devices remains unresolved and requires a deeper investigation of the nuclear-physical nature of fusion reactions.

One of the modern research directions in Nuclear Physics is the study of the generation mechanisms of high-energy neutrons and their interaction with matter in condensed media. The neutron yield parameters in PF devices exhibit a complex multifactorial dependence on the conditions of the fusion process, the ion energy spectrum, and the energy dependence of nuclear reaction cross-sections. The interplay of these factors leads to temporal instability and pulse fluctuations of neutron emission. To overcome these limitations, studying the nuclear kinetics of fusion reactions and optimizing neutron yield parameters is one of the key challenges in nuclear physics. It is also known that neutron generation occurs through both thermonuclear and beam-target (accelerator-like) mechanisms. However, the dominant mechanism and its dependence on specific parameters remain subjects of ongoing debate. Therefore, investigating neutron generation mechanisms and their

experimental modeling is a highly relevant problem in contemporary nuclear physics.

Currently, the interaction of fusion reaction products in PF devices — particularly ion and neutron fluxes with materials leads to radiation erosion and damage, which is of great importance for testing radiation resistance of materials, ensuring nuclear safety, and advancing applied nuclear physics for peaceful purposes. In tungsten (^{182}W) and molybdenum (^{92}Mo) plates, nuclear reactions such as (n,γ) induced by radiation exposure result in the formation of radiation defects in crystal lattices, including dislocations and vacancies. As a consequence, the accumulation of helium and hydrogen isotopes leads to the formation of radiation-induced blisters and microcracks. These effects pose a significant risk for future thermonuclear reactors, reducing their operational lifetime and energy efficiency. Therefore, investigating radiation damage and radiation resistance of materials after exposure is one of the important tasks in nuclear physics.

Taking into account the above-mentioned issues, determining the generation parameters of thermonuclear neutrons in the energy range of 2.5-3 MeV, studying their relationship with fusion reaction kinetics, and conducting a comprehensive experimental analysis of neutron-matter interactions are scientifically significant tasks aimed at solving both fundamental and applied problems of nuclear physics. This defines the relevance of the present dissertation work.

The purpose of the work is to determine the key nuclear-physical parameters affecting the intensity of thermonuclear neutron generation during DD fusion reactions in a plasma focus (PF) discharge, as well as to study radiation-induced structural changes and erosion resulting from their interaction with materials.

To achieve the stated goals, the following ***tasks need*** to be addressed:

– to determine the physical conditions for the realization of DD thermonuclear fusion reactions depending on plasma focus parameters, and to investigate the possibility of generating fast neutrons in the MeV energy range;

– to experimentally study the effect of physical and energy parameters of the PF-4 device on DD thermonuclear fusion reactions and on the nuclear mechanisms of neutron generation;

– to determine the dependence of radiation damage degree and erosion in tungsten (^{182}W) and molybdenum (^{92}Mo) plates on the flux density after exposure to neutron and ion irradiation in the PF-4 thermonuclear experimental device.

Object of research

Neutron emission parameters resulting from DD fusion reactions in the discharge of the PF-4 device, and their nuclear interaction processes with tungsten (^{182}W) and molybdenum (^{92}Mo).

Subject of research

The influence of physical and energy parameters of the plasma focus (PF) device on the kinetic parameters of DD thermonuclear fusion reactions and neutron generation. Displacement of atoms and radiation erosion processes arising from neutron interactions with tungsten (^{182}W) and molybdenum (^{92}Mo).

Research methods

The dissertation employed a comprehensive set of experimental diagnostics and analytical methods aimed at the detailed investigation of plasma processes, thermonuclear reactions, and radiation-induced modifications of material surfaces. In particular, a scintillation detector was used to register hard X-ray radiation generated in the plasma compression (pinch) region. This diagnostic made it possible to detect high-energy radiation associated with the acceleration of charged particles and to analyze the temporal characteristics and intensity of X-ray emission during plasma compression. To determine the absolute neutron yield produced in deuterium–deuterium (D–D) fusion reactions, a neutron detection system based on activated silver foil in combination with a Geiger counter was applied. This method provided a reliable quantitative assessment of neutron production and enabled the evaluation of fusion reaction efficiency under various discharge conditions.

The formation, evolution, and stability of the plasma column were studied using a Videoscan-415-2001 high-speed camera equipped with a CCD matrix. This optical diagnostic allowed real-time visualization of plasma dynamics, including the geometry and temporal development of the plasma column during the discharge. Electrical characteristics of the plasma, specifically the peak discharge current and pinch current, were measured using a Rogowski coil, which ensured accurate, non-invasive registration of fast current pulses and detailed analysis of current waveforms.

To investigate radiation- and plasma-induced morphological changes on material surfaces, a set of advanced microscopy techniques was employed. Preliminary surface observations were carried out using a Leica DM 6000M optical microscope, enabling the identification of macroscopic and microscale features. For high-resolution analysis of surface morphology, microstructure, and defect formation at the micro- and nanoscale, scanning electron microscopy was performed using the SU8200 field-emission SEM (Hitachi High-Technologies Corporation) and the ZEISS Crossbeam 540 SEM. In addition, an atomic force microscope (AFM) was used to study the surface topography in detail, providing quantitative information on surface structure, roughness, and nanoscale features.

To analyze ion–solid interactions and to quantitatively assess radiation-induced damage in materials, numerical simulations were performed using the SRIM (Stopping and Range of Ions in Matter) code. The SRIM software package is based on a Monte Carlo approach and is widely used for calculating the transport of energetic ions in matter, taking into account elastic and inelastic collision processes. Within this dissertation, SRIM calculations were applied to model the penetration depth (projected range), energy loss mechanisms, and spatial distribution of implanted ions in target materials under conditions corresponding to the experimental plasma and ion irradiation parameters. The simulations provided detailed information on electronic and nuclear stopping powers, ion trajectories, and scattering events as a function of ion energy and target composition.

Thesis statements for defense:

1 In the PF-4 plasma focus device, variations in discharge parameters lead to an increase in the energy of deuterium ions during the compression phase, which

enhances the energy-dependent growth of the reaction cross-section σ(E). As a result, the fusion reaction rate increases up to values of $R \sim 10^{16}$-10^{17} $cm^{-3}s^{-1}$. Changes in the nuclear interaction time, in turn, lead to a decrease in the reaction rate and result in neutron generation intensity within the range of $Y_n = 6 \cdot 10^7$-$2 \cdot 10^8$ neutrons per discharge.

2. The variation of anisotropy coefficients in the range of 2.32-2.9, based on the angular distribution of neutrons, indicates that during DD thermonuclear fusion in a plasma focus discharge, the beam-target (accelerator) mechanism plays a dominant role in neutron generation compared to the thermonuclear mechanism.

3. At a damage level starting from 0,3 dpa (displacements per atom), dense blister structures are formed in tungsten due to the accumulation of deuterium ions in vacancy clusters. In the range of 0,6-0,9 dpa, as a result of the coalescence of small-sized blisters, their density decreases by approximately ~65%, while the fraction of large blisters increases by about ~55%. For molybdenum, at damage levels in the range of 0,2-0,6 dpa, surface erosion changes increase by 15-20%.

The scientific novelty of the work:

1. In thermonuclear plasma, the influence of the physical and energy parameters of the plasma focus device on the parameters of the DD thermonuclear fusion reaction has been established, and for the first time, the neutron yield at the level of 10^6-10^8 neutrons per discharge has been experimentally recorded.

2. For the optimal parameters at which the maximum neutron yield is achieved in the PF-4 plasma focus device, the dominant mechanism governing thermonuclear neutron generation was identified.

3. It has been experimentally established that, with increasing radiation interaction of neutron and ion fluxes in the ^{182}W material, starting from a level of 0,6 dpa, the number of dense blisters formed due to the accumulation of deuterium ions in dislocation lattices, vacancies, and interstitial defects decreases. Meanwhile, in the ^{92}Mo material at 0,4 dpa, an increase in the width of microcracks is observed.

The theoretical and practical significance of the research

The results obtained in this dissertation are of significant importance for nuclear research, enabling the development of neutron sources, the determination of key parameters necessary for a deeper understanding of the kinetics of DD nuclear reactions, and the clarification of neutron generation mechanisms. In addition, they provide important scientific and practical value for the experimental modeling of radiation-induced damage and erosion in crystal lattices following neutron–matter interactions, as well as for evaluating the radiation resistance of materials used in high-energy nuclear technologies.

The author's personal contribution lies in the fact that the entire volume of the dissertation work, the selection of the research methodology, the problem-solving approach, and the modernization of the experimental setup were carried out solely by the author. The formulation of tasks and the discussion of the obtained experimental results were conducted in collaboration with the scientific advisors. Zh. Moldabekov participated in all experimental work, thus making the primary contribution to the preparation of all the mentioned scientific papers.

Approbation of dissertation work.

The results obtained in the dissertation were presented and discussed at the following events: Proceedings of the International Conference on Advances and Applications in Plasma Physics (AAPP 2019), Saint Petersburg, Russia, September 18-21, 2019 y. 20th International conference on Radiation Effects in Insulators. Nursultan, Kazakhstan, 19-23 August 2019 y. International Conference of Students and Young Scientists «Farabi Alemi», Almaty, Kazakhstan, April 6-9, 2020 y. «The 2nd International Conference on High Energy Physics, Material Science, and Nanotechnology», International Scientific Conference, Almaty, Kazakhstan, February 15-16, 2024 y. The International Scientific and Practical Conference "Science and Innovations: The Republic of Kazakhstan and International Trends," Nur-Sultan, Kazakhstan, June 2–4, 2020.

Publications. Based on the materials of the dissertation, 16 printed works have been published: 9 in journals from the list of the Committee for Control of Education and Science of the Ministry of Education and Science of the Republic of Kazakhstan; 2 articles in foreign journals with a non-zero impact factor, included in the Web of Science and Scopus international databases; and 5 works in the proceedings of International Scientific Conferences.

Volume and Structure of the Dissertation. The dissertation consists of an introduction, three sections, a conclusion, and a list of 124 references. It contains 101 pages of main text, including 49 figures, 89 formula and 8 tables.