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INTERRELATION OF FUSION CROSS-SECTION, REACTION RATE, AND NEUTRON PRODUCTION IN A D-D REACTION IN A PLASMA FOCUS DEVICE

This study presents an analysis of D-D thermonuclear fusion processes occurring in a plasma focus device by examining the interrelation between fusion cross-section, reaction rate, nuclear reaction time, and neutron production. The goal of the study is to clarify the mechanisms of neutron production from the viewpoint of nuclear reaction kinetics governed by Coulomb barrier penetration and quantum tunneling effects. The fusion cross-section and reaction rate were calculated for deuteron energies in the range of 1-200 keV and compared with nuclear data libraries EXFOR and ENDF. Neutrons produced as a result of the D-D fusion reaction were detected using a silver activation foil detector. The corresponding effective deuterium ion energy region of 25-100 keV for D-D fusion reaction, cross-section 10^{-3}-10^{-2} barn, and a nuclear reaction time of 20-80 ns were obtained. These results are consistent with experimentally observed neutron pulse durations produced during the pinch phase. In this regime, the rate of nuclear fusion reactions in deuterium increases by approximately one order of magnitude compared to Maxwellian plasma, while the requirements for the magnetic confinement parameters of such plasma are significantly reduced.

Keywords: D-D reaction, reaction time, Gamow factor, neutron production, fusion plasma, reaction rate.

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Плазмалық фокус қондырғысындағы D-D реакциясындағы синтезделу қимасы, реакция жылдамдығы мен нейтрондар генерациясы арасындағы өзара байланыс

Бұл жұмыста плазмалық фокус қондырғысында жүзеге асатын D–D термоядролық синтез процестері синтез қимасы, реакция жылдамдығы, ядролық реакция уақыты және нейтрон генерациясы арасындағы өзара байланыс негізінде талданды. Зерттеудің мақсаты - Кулондық тосқауылдан өту және кванттық туннельдеу әсерлерімен анықталатын ядролық реакция кинетикасы тұрғысынан нейтрондардың түзілу механизмдерін айқындау болып табылады. D-D синтез реакциясының қимасы мен реакция жылдамдығы дейтрон энергиясының 1-200 кэВ аралығында есептеліп, EXFOR және ENDF ядролық деректер қорларымен салыстырылды. D-D синтез реакциясы нәтижесінде пайда болған нейтрондар күміс фольгалы активациялық детектор көмегімен тіркелді. Зерттеу нәтижесінде D-D синтезделу реакциясы үшін тиімді дейтерий иондарының энергия аймағы 25-80 кэВ екендігі анықталды. Синтез қимасы 10^{-3}-10^{-2} барн аралығында болады, ал ядролық реакция уақыты 20-80 нс мәндерін қабылдап, сығылу фазасында эксперименттік тіркелген нейтрон импульстерінің ұзақтығымен сәйкес келетіні көрсетілді. Бұл жағдайда импульсті термоядролық плазмасындағы синтез реакциясының жылдамдығы Максвеллдік плазмамен салыстырғанда артады және плазманы магниттік ұстап тұру параметрлеріне қойылатын талаптар айтарлықтай төмендейтіні анықталды.

Түйін сөздер: D-D реакциясы, реакция уақыты, Гамов факторы, нейтрон генерациясы, термоядролық плазма, реакция жылдамдығы.

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Взаимосвязь сечения синтеза, скорости реакции и генерации нейтронов в D-D реакции в плазмофокусном устройстве

В данной работе представлен анализ термоядерных процессов D-D синтеза, протекающих в плазма фокусном устройстве, на основе исследования взаимосвязи между сечением синтеза, скоростью реакции, временем протекания ядерной реакции и генерацией нейтронов. Целью исследования является выяснение механизмов образования нейтронов с точки зрения кинетики ядерных реакций, определяемой проникновением через Кулоновский барьер и эффектами квантового туннелирования. Сечение и скорость D-D реакции синтеза были рассчитаны в диапазоне энергий дейтронов 1-200 кэВ и сопоставлены с ядерными библиотеками данных EXFOR и ENDF. Нейтроны, образующиеся в результате D-D реакции синтеза, регистрировались с использованием серебряного активационного фольгового детектора. Установлено, что эффективная ионная энергетическая область для D-D синтеза составляет 25-80 кэВ при значениях сечения 10^{-3}-10^{-2} барн, а время ядерной реакции находится в диапазоне 20-80 нс, что согласуется с экспериментально наблюдаемой длительностью нейтронных импульсов в пинч фазе. Показано, что в данном случае скорость термоядерных реакций в дейтериевой плазме возрастает по сравнению с Максвелловской плазмой, при этом требования к параметрам магнитного удержания существенно снижаются.

Ключевые слова: D-D реакция, время реакции, фактор Гамова, генерация нейтронов, термоядерная плазма, скорость реакции.

Introduction

Nuclear fusion reactions occur when light nuclei approximation each other sufficiently closely under the action of nuclear forces. This process requires overcoming the electrostatic Coulomb barrier that produces mutual repulsion between positively charged nuclei. During fusion, the mass defect is converted into released energy, making fusion a powerful source of thermonuclear energy [1, 2]. For a typical nuclear radius of $R_0 \approx 5\cdot10^{-15}$ m, the Coulomb barrier energy can be estimated as $E_b \approx 0.28\, Z_1Z_2$ MeV. However, due to the quantum tunneling effect, fusion reactions may occur even at particle energies lower than the barrier height [3]. For hydrogen isotopes, the Coulomb barrier is approximately 0.28 MeV. To overcome this barrier, plasma particles must be accelerated to sufficiently high velocities, providing the kinetic energy required for close nuclear approach [4]. In plasma focus (PF) reactors, the discharge chamber is filled with deuterium or tritium gas [5-7]. When charged by a high-voltage pulse, deuterium ions can be accelerated up to velocities of 10^7-10^8 m/s. Collisions between such high-energy ions increase the fusion reaction cross-section, leading to energy release through light-nuclei fusion processes, primarily the D-D and D-T fusion reactions:

$$\mathrm{D + T \rightarrow n(14{,}1\ MeV) + He^4(3{,}5\ MeV)}, \quad (1)$$

$$\mathrm{D + He^4 \rightarrow p(14{,}68\ MeV) + He^4(3{,}67\ MeV)}, \quad (2)$$

$$\mathrm{D + D \rightarrow p(3{,}02\ MeV) + T(1{,}01\ MeV)}, \quad (3)$$

$$\mathrm{D + D \rightarrow n(2{,}45\ MeV) + He^3(0{,}817\ MeV)}. \quad (4)$$

The fusion reaction cross-section is defined by the number of reactions occurring per unit time due to the flux of incident particles interacting with target nuclei and represents one of the fundamental parameters characterizing fusion reactivity and reaction rate. Now days important to study neutron production in pulsed plasma phenomena for improve the performance of D-D fusion reactions in plasma focus devices. Understanding the relationship between the dynamical behavior of particles and neutron production from D-D fusion reactions enables optimization of reactor parameters and enhanced neutron yield [8-10].

Detection of D-D fusion reaction products and practical applications represents one of the important problem of modern experimental nuclear physics, nuclear engineering and thermonuclear research. Plasma focus device is experimental thermonuclear reactor which is capable of neutron production in the range of 10^6-10^{12} neutrons per pulse, when filled deuterium or deuterium-tritium gas mixture in chambers [11-13]. Therefore, to study and optimization of basic parameters of efficiency D-D fusion reaction and increase neutron production, still remain critical objectives in such experimental fusion systems.

It is necessary to analysis to influence of energetically parameters PF device, such as discharge current, gas pressure, and charging voltage to evaluation of the fusion cross-section, reaction time and reaction rate in D-D fusion reactions. These parameters significantly affect of collision particles in thermonuclear plasma and efficiency of nuclear reactions and neutron production [14, 15]. In dense plasma focus device, the thermonuclear plasma compression (pinch) phase occurs an extremely short time interval, typically on the order of several tens of nanoseconds. Therefore, as a first approximation, the application of a zero-dimensional (0D) phenomenological model is justified for describing the fusion process.

The purpose of this study is to determine the optimal values of the key parameters influencing the D-D fusion reaction rate and neutron production in a plasma focus reactor in order to improve overall fusion efficiency.

Research мethodology

The nuclear reaction rate represents the number of nuclear reactions that occur in a unit volume of fusion plasma per unit time. For the D-D fusion reaction, the reaction rate can be written in the following form:

$$R(E) = \frac{1}{2} n_d^2 \sigma(E) \vartheta(E), \qquad (5)$$

where n_d is the deuterium ion concentration, $\sigma(E)$ is the energy-dependent fusion cross-section and $\vartheta(E)$ represents the ion velocity. In the low-energy region (0-200 keV), the fusion cross-section was approximated using the Gamow factor. According to the 0-Dimensional Phenomenological Fusion Rate Model Based on Gamow Reactivity, the Gamow cross-section σ represents the effective interaction area of the reaction and characterizes the probability of interaction between a pair of particles per unit volume during a thermonuclear fusion process. For D-D thermonuclear reactions, the Gamow fusion cross-section can be written as follows:

$$\sigma(E) = \frac{S(E)}{E} exp\left(-\frac{E_G}{E}\right)^{1/2}, \quad (barn) \quad (6)$$

where E is the kinetic energy of interacting particles in the center-of-mass in the range (0:200) keV for D-D reaction. E_G is Gamow parameter. For the D-D fusion reaction the astrophysical S-factor, given by the following formula

$$S(E) = \alpha_1 + E\left(\alpha_2 + E\big(\alpha_3 + E(\alpha_4 + E\alpha_5)\big)\right). \quad (7)$$

The constant parameters for the fusion cross-section: E_G = 31.3970 кэВ$^{1/2}$, α_1 =5.3701·10^4, α_2= 3.3027·10^2, α_3=–1.2706·10^{-1}, α_4 = 2.9327·10^{-5}, α_5 =–2.5151·10^{-9}.

In a plasma focus device, the gas pressure related to the nuclear reaction rate through the ion density. Since the working gas becomes ionized during the discharge process, the ion density during the compression phase can be approximately $n_d \sim n \approx p$ expressed as:

$$n = \frac{p}{kT}, \qquad (8)$$

where Boltzmann constant k = 1.38·10^{-23} joule /mole. T is temperature in K. Therefore, taking into account the variation of the working gas pressure in the chamber, the nuclear reaction rate (1) equation can be expressed by the following relation:

$$R \approx p^2(\sigma\vartheta). \qquad (9)$$

An increase in the working gas pressure in the chamber leads to a higher density of deuterium ions in the plasma, thereby increasing the number of particles participating in nuclear reactions. According to the ideal gas law, the deuterium ion density is directly proportional to pressure. Therefore, the D–D fusion reaction rate increases approximately following the scaling law $R \approx n_d^2 \approx p^2$. However, excessively high pressure leads to reduce the ions acceleration energy in the fusion plasma, which in turn decreases the effective fusion cross-section.

Considering the expression presented above, an increase in gas pressure leads to an increase in fusion plasma density, while the ion temperature decreases under fixed discharge energy conditions. This reduction in temperature lowers the Gamow tunneling probability. According to the Zero-Dimensional Gamow-Based Scaling Model [16, 17] the fusion reaction rate can therefore be expressed in the following form:

$$R(p) \approx p^2 exp\left(-\alpha p^{\frac{1}{3}}\right), \quad (10)$$

where α is the pressure-adapted parameter of the Gamow exponential factor.

$$\alpha \approx \sqrt{\frac{E_G}{E_{eff}}}, \quad (11)$$

where E_{eff} is effective energy particles and $\exp(-\alpha p^{1/3})$ represents the reduction of nuclear tunneling probability with increasing pressure. The balance between these competing effects indicates that the neutron yield $Y(p) \sim R(p)$ reaches a maximum at an optimal gas pressure.

To register neutron particles produced because of the D–D fusion reaction, a silver activation foil detector (diameter 13.6 cm, cylindrical length 20 cm; detection efficiency ~$1.4\cdot10^{-3}$) was used. In order to slow down fast neutrons generated during the fusion process, the Geiger counter was surrounded by a paraffin moderator. The activated silver foil detector consisted of natural silver ^{107}Ag 51.35 % and ^{109}Ag 48.65 % containing the isotopes. The primary nuclear reactions between neutrons and natural silver occur through neutron capture processes.

$$Ag^{107}(n,\gamma)Ag^{108}(T_{0.5} = 142.9\ s) \rightarrow Cd^{108} + \beta^-(97.2\%), \quad (12)$$

$$Ag^{109}(n,\gamma)Ag^{110}(T_{0.5} = 24.6\ s) \rightarrow Cd^{110} + \beta^-(99.7\%). \quad (13)$$

The detector calibration was performed using a standard Americium–241/Beryllium neutron source with a neutron yield of $1.5\cdot10^7$ neutrons/s.

Results and discussion

Evaluation of neutron production and fusion reaction rate necessary precise determination of the deuteron energy-dependent total cross-section of the D-D fusion reaction. In this work, the dependence of the total D-D reaction cross-section on E ion energy was calculated within the energy range of 1-200 keV according to Eq.(2). The averaged cross-section of the D-D fusion reaction is shown in Figure 1.

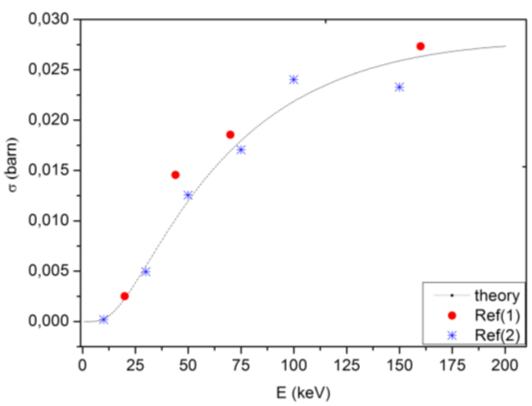


Figure 1 – Total cross-section of the D-D reaction. The calculated values (line) are compared with nuclear EXFOR (Ref1) and ENDF (Ref2) databases

The reaction cross sections used in the calculation of the fusion reaction rate were adopted from the EXFOR database [18], and the recommended evaluated data were taken from the ENDF/B-VIII.0 nuclear data library [19]. In the E_{eff}=25-80 keV range, theoretical and experimental results agree well. In the E_{eff} =100-150 keV interval, slight differences are observed, which can be attributed to the energy dependence of the astrophysical S-factor and experimental uncertainties inherent in the various measurements.

For plasma focus device calculated α parameter in the range E_{eff}=20-80 keV, and equal $\alpha \approx$ 14-15. The obtained constant value $\alpha \approx$ 14-15 is consistent with nuclear fusion theory and previously reported D-D reactivity studies. Since the parameter α is directly related to the Gamow tunneling factor, its invariance indicates that neutron production in plasma focus devices is governed primarily by nuclear-scale Coulomb barrier penetration rather than macroscopic discharge parameters. Similar effective energy ranges reported by Bosch and Hale (E_{eff}=30-100 keV $\alpha \approx$ 12-18) [16, 20] and Nevins and Swain (E_{eff}=30-100 keV, $\alpha \approx$ 12-18) [18, 21] confirm that D-D fusion reactions occur within a narrow Gamow window, leading to an approximately constant tunneling parameter.

The fusion cross-section of the D–D reaction remains extremely small at low ion energies due to the presence of the Coulomb barrier, which significantly limits the probability of nuclear interaction. With increasing ion energy, the tunneling probability through the Coulomb barrier rises rapidly, leading to a pronounced growth in neutron yield that is predominantly governed by nuclear effects, particularly the increase of the fusion reaction cross-section. In this work, the application of experimentally measured nuclear data from the EXFOR database together with evaluated datasets from the ENDF library enhances the accuracy and reliability of fusion reaction rate calculations, ensuring a physically consistent interpretation of neutron generation and nuclear processes occurring in plasma focus devices.

In the fusion plasma, the reaction rate depends on the number densities of deuterium (n_1 and n_2), the reaction cross section (σ), and the relative velocity (υ) because ions have distribution of velocities. In Figure 2 shown the D-D reaction rate over ion energy range 0-200 keV for 2-4 Torr deuterium gas pressure.

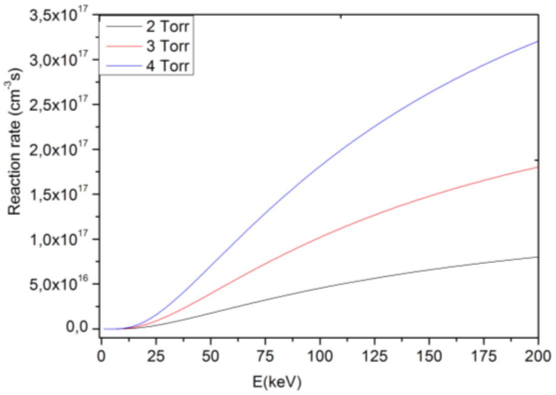


Figure 2 – Reaction rate of the D-D fusion process as a function of deuteron energy at different filling gas pressure

As shown in the figure, the D-D fusion reaction rate increases monotonically with increasing deuteron energy for all considered gas pressures. This behavior is explained by the exponential dependence of the fusion cross-section on the quantum tunneling probability through the Coulomb barrier. An increase in gas pressure from 2 to 4 Torr leads to a higher deuterium ion density in the plasma, resulting in a significant enhancement of the reaction rate over the entire investigated energy range. From the viewpoint of nuclear kinetics, this behavior is consistent with the scaling relation $R \approx n_d^2 \approx p^2$ indicating that an increase in particle concentration raises the frequency of nuclear collisions. Furthermore, in the low-energy region ($E < 30$ keV), the reaction rate changes slowly due to the low tunneling probability, whereas in the 50-200 keV range a rapid increase in reaction intensity is observed. This indicates the formation of an effective energy window for fusion, demonstrating that neutron generation in plasma focus devices is governed by coupled energy-density conditions within the thermonuclear plasma.

Neutron production is one of the most important indicators of D-D fusion reactions in plasma focus device. Figure 3 shows the neutron emission as function of charging voltage and gas pressure.

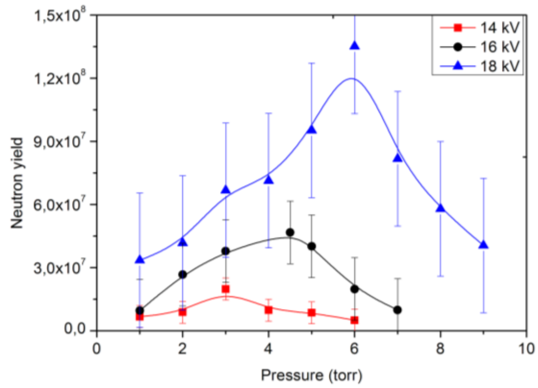


Figure 3 – The dependence of neutron production at different gas pressure on D-D fusion reaction

As shown in Figure 3, the formation of a maximum in neutron yield as a function of gas pressure is associated with the exponential energy dependence of the D-D fusion cross-section. This dependence is governed by Gamow-type quantum tunneling through the Coulomb barrier and, together with the quadratic density scaling of plasma particles predicted by nuclear reaction theory, determines the neutron production behavior.

Neutron production in plasma focus devices results from the relation between macroscopic electrical discharge processes and microscopic nuclear interactions. During the discharge, a high-amplitude pulsed current I is formed, and due self-generated magnetic field compresses the fusion plasma to high density and temperature conditions [22-24]. At this stage, strong electromagnetic fields and fusion plasma instabilities influence accelerate deuterons. The increase of ion energy enhances the probability of quantum tunneling through the Coulomb barrier, leading to an increase in the effective cross-section of the D-D fusion reaction.

The neutron generation time during D-D fusion reaction expressed as following:

$$\tau_n = \frac{1}{R}. \tag{14}$$

Thus, an increasing the R reaction rate leads to a reduction of neutron production time. This indicating that, the D-D reaction in fusion plasma more intensively occurs within a short time interval. This result shows that neutron production increases simultaneously with rising fusion plasma density and ion energy. The experimental research work [25-27] indicated that τ_n neutron production time corresponds to fusion plasma compression Δt_n time interval ($\tau_n \approx \Delta t_n$) during D-D fusion reactions. In plasma focus devices, the neutron production time is determined from the temporal width of the neutron pulse recorded by a fast neutron detector. The full width at half maximum (FWHM) of the neutron signal characterizes the effective duration of nuclear fusion reactions occurring during the pinch phase and is directly related to the fusion reaction rate in the plasma.

Figure 4 shows experimentally results variation of the average nuclear reaction time in the fusion plasma column, as a function of deuterium gas pressure in the discharge chamber and charging voltage.

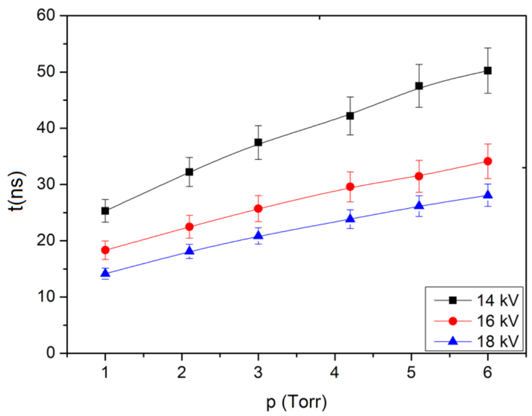
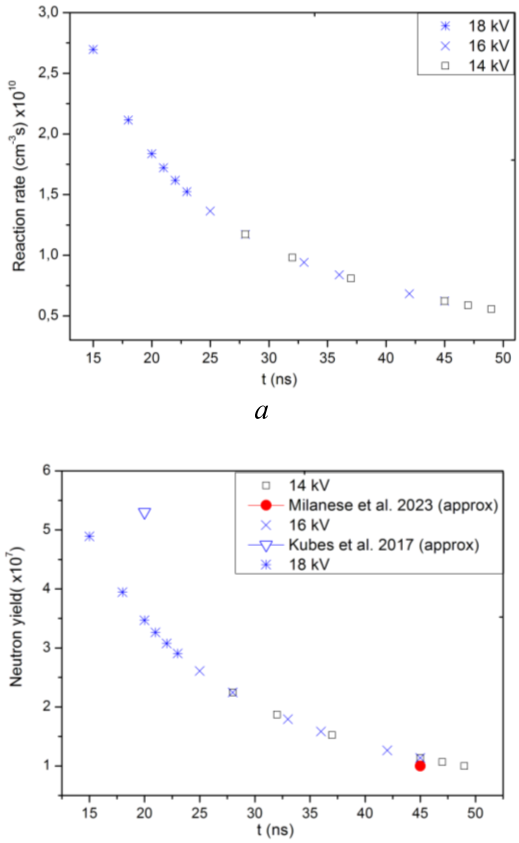


Figure 4 – Variation of the nuclear reaction time in the fusion plasma column

As shown in the Figure 5, the dependence of nuclear reaction duration on gas pressure is defined by variations in deuterium ion density and energy exchange processes within the fusion plasma. An increasing gas pressure, plasma density rises, and the enhanced collision frequency promotes stronger thermal energy redistribution, thereby extending the lifetime of the effective fusion region. Moreover, under higher pressure conditions, the dynamics of the current sheath become slower, and the increased stability of the pinch phase contributes to a longer duration of nuclear reactions. Thus, the pressure-dependent variation of reaction time reflects the coupled interaction between fusion plasma hydrodynamics and the nuclear kinetics of the D-D fusion process.

When fusion plasma compression with magnetic field, the radius of fusion plasma column decreases to r_p = 0.5-0.8 cm. It is leading to an increase deuterium ion density n_d and nuclear collisions per unit time, thereby intensifying the fusion process. Consequently, the fusion reaction rate R and neutron production begins to rise. The variation of fusion reaction rate dependence of fusion time and neutron yield are shown in Figure 5.

The quantitative results presented in figure-5 clearly demonstrate that both the nuclear reaction rate and neutron yield are directly dependent on the reaction duration. For example, in the 18 kV operating regime, at a reaction time of t≈15 ns, the reaction rate reaches approximately $2.5\cdot10^{20}$ $cm^{-3}s^{-1}$ - $2.8\cdot10^{20}$ $cm^{-3}s^{-1}$, with a corresponding neutron yield of about $4\cdot10^7$ n/discharge - $5\cdot10^7$ n/discharge. When the reaction time increases from 40 ns to 45 ns, the reaction rate decreases to approximately from $0.8\cdot10^{20}$ $cm^{-3}s^{-1}$ to $0.6\cdot10^{20}$ $cm^{-3}s^{-1}$, while the neutron yield correspondingly decrease nearly $1.5\cdot10^7$ n/discharge - $1\cdot10^7$ n/discharge. These results indicate that during the short-lived pinch phase, the plasma density and ion energy reach their maximum values, significantly increasing the probability of nuclear collisions and ensuring intense neutron generation. Thus, the reduction of reaction time enhances fusion efficiency and confirms that neutron production in plasma focus devices occurs predominantly in a highly reactive, short-duration nuclear burn regime.



a

b

Figure 5 – Correlation between fusion reaction rate (a) and neutron production (b) as a function of nuclear reaction time in plasma focus discharges

Experimental and literature data [15, 18, 25] further show that the Nanofocus device operates at low pressure and short pinch duration, producing neutron yields on the order of ~10^6 neutrons pulse, which is consistent with the predicted t_p region obtained in the present experimental and modeling results. In addition, the work of Kubes et al. [28] reports neutron yields of approximately (0.8-5.3)·10^7 neutrons/ pulse for the PF-200 device. This comparison demonstrates that, as predicted by the analytical model, neutron yield increases with decreasing pinch duration. The observed trend shows qualitative agreement with experimental results obtained in both the Nanofocus system (Milanese et al.,) [29] and the PF-200 device (Kubes et al.,) [28].

In summary the experimentally observed pressure maximum and voltage scaling are governed by the energy dependence of the D-D fusion cross-section through Gamow tunneling. The variation of reaction time provides the effective nuclear interaction time during which fusion reactions occur.

Conclusion

In this work, the nuclear-physical characteristics of D-D thermonuclear fusion in a plasma focus device were analyzed by correlating the fusion cross-section, reaction rate, nuclear reaction time, and neutron emission parameters using both numerical evaluation and experimental observations. The calculated fusion cross-section in the deuteron energy range of 1-200 keV reaches values of $\sigma(E)\sim10^{-3}$-10^{-2} barn and compared with evaluated nuclear data libraries EXFOR and ENDF. Also, determined the fusion reaction rate increases quadratically with density and reaches values on the order of $R\sim10^{16}$-10^{17} $cm^{-3}s^{-1}$ in the effective energy region 25-100 keV. The obtained results demonstrate that the increase of ion energy significantly enhances the fusion probability through Coulomb barrier tunneling, thereby intensifying neutron production in the compressed fusion plasma column.

The main scientific outcome of this study is the establishment of a consistent relationship between fusion reaction rate, neutron production time, and neutron yield within a unified nuclear kinetics framework. It is shown that an increase in reaction rate corresponds to a reduction of the effective nuclear reaction time, leading to the formation of intense nanosecond neutron pulses experimentally observed in plasma focus systems. These findings of the work provide a nuclear-physics based interpretation of neutron production optimization and improving predictive models for thermonuclear fusion systems, neutron sources which application for advanced nuclear science and applied fusion technologies.

Author Contributions

Zh. Moldabekov: Conceptualization, Visualization, Investigation, Writing – Original Draft. **A. Zhukeshov**: Supervision, Validation, Funding acquisition, Writing – Review & Editing. **A. Gabdullina**: Formal Analysis, Project administration, Methodology. **A. Amrenova**: Resources, Visualization

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