Abstract — The review describes physical principles underlying efficient production of free neutrons, up-to-date possibilities and prospects of creating fission and fusion neutron sources with intensities of $10^{15}$–$10^{21}$ neutrons/s, and schemes of production and application of neutrons in fusion–fission hybrid systems. The physical processes and parameters of high-temperature plasmas are considered at which optimal conditions for producing the largest number of fusion neutrons in systems with magnetic and inertial plasma confinement are achieved. The proposed plasma methods for neutron production are compared with other methods based on fusion reactions in nonplasma media, fission reactions, spallation, and muon catalysis. At present, intense neutron fluxes are mainly used in nanotechnology, biotechnology, material science, and military and fundamental research. In the near future (10–20 years), it will be possible to apply high-power neutron sources in fusion–fission hybrid systems for producing hydrogen, electric power, and technological heat, as well as for manufacturing synthetic nuclear fuel and closing the nuclear fuel cycle. Neutron sources with intensities approaching $10^{20}$ neutrons/s may radically change the structure of power industry and considerably influence the fundamental and applied science and innovation technologies. Along with utilizing the energy produced in fusion reactions, the achievement of such high neutron intensities may stimulate wide application of subcritical fast nuclear reactors controlled by neutron sources. Superpower neutron sources will allow one to solve many problems of neutron diagnostics, monitor nano- and biological objects, and carry out radiation testing and modification of volumetric properties of materials at the industrial level. Such sources will considerably (up to 100 times) improve the accuracy of neutron physics experiments and will provide a better understanding of the structure of matter, including that of the neutron itself.

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1. INTRODUCTION

Powerful neutron sources are high-tech devices with unique physical and engineering parameters [1–3]. These devices are designed for the production of one of the most mysterious matter species—neutrons—and represent a tool that opens wide capabilities for modifying the elemental composition of matter, release of nuclear energy, and penetration into solid media.

The composition of chemical elements alters in nuclear reactions that occur on spatial scales on the order of a few femtometers (1 fm = $10^{-15}$ m). In most nuclear reactions, neutrons play a governing role. The physical size of a free neutron is about 1.14 fm, while the dimensions of nuclei of chemical elements vary from 0.42 fm for a proton to 15 fm for a uranium nucleus [4]. Taking into account typical dimensions of particles involved in nuclear reactions, the application of processes occurring on femtometer scales can naturally be called femtotechnology. Note that, in nanotechnological processes involving much larger structures with dimensions of $\sim 10^{-9}$ m, the composition of chemical elements remains unchanged.

Femtotechnology corresponds to the level to which modern science can penetrate deep into matter and at which the dreams of medieval alchemists can be implemented. Using spallation reactions initiated by a fast proton beam, it is possible not only to solve the problem of transmutation of lead into gold, but also to produce any chemical element from lead, mercury, or tungsten (see Fig. 1 [5]).

Various processes involving neutrons, such as nuclear reactions, inelastic interaction with nuclei, and elastic scattering, in which the wave nature of neutrons manifests itself (the de Broglie wavelength is $\lambda = h/mv$, where $h$ is the Planck constant and $m$ and $v$ are the mass and velocity of a neutron, respectively), open unique diagnostic capabilities. Irradiation of matter by fast and cooled neutrons makes it possible to investigate the structure of large dense objects, while enhanced neutron scattering by light atoms allows one to study the fine structure of hydrocarbon compounds and biological objects. That a neutron possesses a magnetic moment is quite helpful for studying the magnetic structure of materials [6].

The state of the physics and technology of superpower neutron sources was considered in detail in the framework of the ANS and SNS projects, aimed at achieving the highest possible neutron yields in fission reactors and accelerator sources based on spallation reactions [7–9]. Problems of creating low- and mod-
erate-power sources were analyzed in the framework of the IAEA project [10]. Volumetric neutron sources based on spherical tokamaks and intended for testing structural materials to be used in fusion reactors were analyzed in the framework of component test facility (CTF) projects at ORNL [11] and UKAEA [12], as well as in the framework of the ARIES project [13]. The problem of a tokamak operating as a neutron source for solving nuclear technology tasks of the U.S. fusion program was recently considered in [14].

Accelerator neutron sources were also thoroughly discussed in hybrid system design studies [15, 16], including the so-called “neutron factory” [17]—a research source based on a linear accelerator in the last stage of which neutrons are multiplied in the subcritical assembly of a fission reactor.

Vast experimental data obtained so far in nuclear reactors and accelerators, as well as the design studies on high-power neutron sources, indicate that the neutron yield of systems based on fission and spallation reactions saturates at a level of $10^{18}$ neutrons/s [10].

In recent years, interest in the development of fusion-based neutron sources has increased considerably. Conferences [18–20] and meetings [21] have demonstrated great interest in the elaboration of high-power neutron sources and their implementation in science and technology. According to [22–24], tokamak-based neutron sources can, in principle, provide intensities higher than $10^{18}$ neutrons/s. It is expected that an intensity of $10^{20}$ neutrons/s will be achieved in ITER at a pulse duration of 3000 s [25]. Microexplosions in ICF systems are also regarded as promising pulsed neutron sources [1].

In the present survey, we discuss the possibilities and prospects of the development of fusion neutron sources with intensities of $10^{15}–10^{21}$ neutrons/s, as well as hybrid neutron sources based on fusion–fission hybrid (FFH) systems. Special emphasis is put on tokamak-type magnetic confinement systems. To determine the role of FFH systems as high-power sources of neutrons, they are compared with contemporary systems based on other principles.

Here, we do not discuss high-power pulsed neutron sources based on high-energy accelerators, such as the Large Hadron Collider [26], and superpower deuterium-bomb neutron sources with explosion energies of up to 100 kton TNT equivalent, the capabilities of which (mainly power-producing ones) were analyzed in detail in [27].

Section 2 describes the most efficient reactions of neutron production that are used in existing systems and those under design, as well as reactions leading to neutron losses. Comparison of the neutron and energy balance in these reactions is made in Section 3. Possible applications of neutron sources are discussed in