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A 15-YEAR FORWARD LOOK AT NEUTRON FACILITIES IN **JINR**

A report to the Programme Advisory Committee
for Condensed Matter Physics of JINR, January 19, 2017

Аксенов В. Л. Е3-2017-12
Источники нейтронов ОИЯИ через 15 лет

Технический ресурс реактора ИБР-2, одного из ведущих импульсных источников нейтронов в мире, заканчивается в 2032 г. Обсуждаются варианты концепции нового источника и его место в мировом нейтронном ландшафте. Анализируются современные тенденции развития наук, где используются нейтроны. Предложены приоритетные эксперименты для нового источника в исследованиях конденсированного вещества, в фундаментальной и ядерной физике.

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Aksenov V. L. E3-2017-12
A 15-year Forward Look at Neutron Facilities in JINR

The service life of the IBR-2 reactor, one of the leading pulse neutron sources in the world, is expected to end in 2032. Modern trends in sciences where neutrons are used, possible variants of a concept for a new neutron source and its potential position in the world neutron landscape are discussed. The flagship experiments for a new neutron source in the fields of condensed matter research, fundamental and nuclear physics are proposed.

The investigation has been performed at the Frank Laboratory of Neutron Physics, JINR.

Communication of the Joint Institute for Nuclear Research. Dubna, 2017

INTRODUCTION

The service life of the IBR-2 reactor, one of the leading pulse neutron sources in the world, is expected to end in 2032. The project was proposed in 1968, the civil construction was started in 1972, and in 1982 the reactor was put into operation. In the period of 2006–2011 the refurbishment was performed, and since 2012 it has been in regular operation. The refurbishment has become possible due to the support of the RF Atomic Energy Ministry which paid the work of its enterprises involved in the process. This payment made up 50% of the whole cost. This support appeared as the result of more than ten years of discussions on the rationale of the necessity of the reactor operation and research programme.

The natural question arises: what is the future of neutron research in JINR? We should keep in mind the following few points. First, the expected service life of the IBR-2 reactor building will end in 2035. It means that the next neutron source must be built on a new place. Second, recently performed calculations [1] show that it is hardly possible to radically improve the essential parameters of the IBR-2 reactor. The present pulse neutron flux density is $\Phi_p = 7 \cdot 10^{15}$ $\mathrm{cm}^{-2} \cdot \mathrm{s}^{-1}$, and theoretically it can be increased up to 10^{16} $\mathrm{cm}^{-2} \cdot \mathrm{s}^{-1}$. The present averaged-in-time neutron flux density on the surface of the water moderator can be increased up to 10^{13} $\mathrm{cm}^{-2} \cdot \mathrm{s}^{-1}$. Third, modern science nowadays and especially 20 years after requires the values of one order of magnitude higher. So, if we look 15–20 years ahead we should think about a new neutron source of preferably fourth generation. Two main criteria are the upper limit parameters and the creation of infrastructure for advanced experiments in complex with the source itself. Nowadays, there is only one source of this type, the European Spallation Source (ESS), which is under construction in Lund (Sweden).

The ESS project was the first project of a neutron source of the fourth generation. The discussions on this source were started in the early 1990s. It was a great wish of the European neutron society to have such a high-level source. A huge amount of work was done to provide a rationale for the project, but it was stopped because of a strong contra activity of ISIS physicists who promised better parameters at the second target at ISIS. During the following years two new spallation sources were constructed: SNS in Oak Ridge (USA) in 2006 and JPARC in Ibaraki (Japan) in 2009. These two sources, together with ISIS and IBR-2, form a club of the world's most intense pulsed neutron sources. The construction of the ESS with the first target station — the third-generation neutron source (for details see Sec. 2) — was started in 2014; first neutrons are expected in 2019.

The long-term prospects of neutron sources in JINR were discussed during the previous 44th PAC session (July 2016), and PAC suggested that FLNP would prepare a report on the following points: modern trends in sciences where neutrons are used, possible variants of a concept for the new neutron source and its potential position in the world neutron landscape. Below, I follow this recommendation.

1. HORISONS OF NEUTRON RESEARCH

Neutrons are used for studying fundamental symmetries and interactions, structure and properties of nuclei, but nowadays neutrons are mostly required in investigations of condensed matter including solid states, liquids, biological systems, polymers, colloids, chemical reactions, engineering systems, etc. What mainly underpins our present-day quality of life depends upon our understanding and consequent control of the behavior of materials. The neutron is, in many ways, an ideal probe for investigating materials, having significant advantages over other forms of radiation in the study of microscopic structure and dynamics.

Nobody can predict scientific challenges 15–20 years ahead. We can, however, extrapolate from the present and foresee where major advances might be possible. In my overview "Neutron physics entering the 21st century" published in 2000 [2], the prospects to solve most important and principal problems in neutron physics were analyzed. Most of the problems mentioned in it are still of current interest. Here, I will emphasize some unsolved tasks and new challenges.

1.1. Condensed Matter Research. Nowadays, more than 90% of extracted neutron beams are used for condensed matter research related to a wide variety of scientific fields such as solid state physics, soft matter (complex liquids, non-crystalline solids, polymers), chemistry, molecular biology, material sciences, and engineering sciences. New fields of research constantly appear. For example, one can mention the recently growing interest in the structure and properties of food and objects of cultural heritage. Over the past years, a number of new problems have appeared in all the above-mentioned sciences where neutron scattering can provide very useful information on the structure and dynamics. Practically every new phenomenon and new material (especially in solid state physics) is probed by neutrons at an early stage of research. Recent results and new tendencies in the research programme at IBR-2 have been lately reviewed [3].

An example of the successful research performed at IBR-2 is the precise diffraction investigations of the crystalline and magnetic structures of Hg-based high-temperature superconductors synthesized in the group of E. Antipov at the

Lomonosov Moscow State University (MSU). The use of the High Resolution Fourier Diffractometer (HRFD) proposed and constructed in FLNP [4] resulted in the development of a microscopic model of this phenomenon by N. Plakida [5] from the Bogoliubov Laboratory of Theoretical Physics of JINR. One more example concerns the Real-Time Diffraction (RTD) method proposed in FLNP [6], which makes it possible to investigate transitional and irreversible processes playing a crucial role in chemistry and biology. Recently, the investigations of electrochemical processes in Li-based batteries were performed in cooperation with MSU [7], which is very important for the energy storage industry.

Condensed matter being a system with an infinite number of degrees of freedom similar to the particle world is a permanent source of new phenomena. From this point of view, the main strategy of any user research center based on a large facility consists of the development and construction of advanced experimental techniques and instruments to be ready for new challenges and to attract more scientists from different research centers with original proposals. The above-mentioned HRFD and RTD instruments provide the realization of such advanced methods. Both of them will have much more possibilities at a neutron source more intense than the IBR-2 reactor. A very important method, inelastic neutron scattering, is very difficult for realization at IBR-2. Investigations of atomic and molecular dynamics are an important tool for neutron scattering, and for full-scale experiments a neutron flux of one order higher than that at IBR-2 is crucial. Nowadays, small-angle scattering and reflectometry are becoming more and more popular. A more intense neutron source will be a source of new scientific opportunities. Some of them are listed below.

In condensed matter physics: nanocrystals, low-dimensional systems, magnetism and superconductivity**.** **In chemistry:** *in situ* real-time measurements for synthesis of novel materials. **In Earth and environmental sciences:** structural studies of complex minerals at high temperatures and high pressures for the understanding of basic geological processes. **In engineering sciences:** nondestructive control of engineering products and machine components to improve industrial technologies. **In soft matter research:** structural and real-time studies of polymers, colloids, liquid crystals, nanoliquids for a lot of industrial processes. **In biology and biotechnology:** structural studies of macromolecular complexes, kinetic measurements during DNA synthesis, drug mobility, etc.

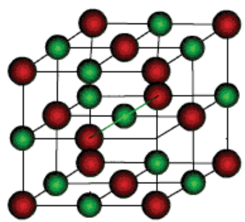
In the 21st century, bioscience will become one of the most rapidly developing areas of research, providing solutions to major challenges facing humankind. Today, we have considerable progress in deciphering the nature and the origin of problems concerning human health. Another significant goal is to understand the processes of life itself at the most fundamental level. One of the most important approaches is to make use of techniques that allow scientists to “see” the structure and dynamics of biologically significant materials at the atomic and molecular scale in the ideal case under conditions as close to physiological as possible. There are several complementary methods — X-ray and neutron scattering, nuclear magnetic resonance (NMR) and electron microscopy — which are used together to determine the shape and internal structure of bioactive molecules such as proteins, as well as to understand the mechanisms of their functioning. By using X-ray crystallography, one can determine the positions of atoms in very small crystals containing large numbers of identical proteins. NMR methods allow one to obtain three-dimensional structures of proteins in solutions or in solid environment. Also, cryoelectron microscopy gives images of the overall shape of large complexes of biological molecules due to the possibility of measurements in water, the natural media for life objects.

Neutrons, like X-rays, reveal a microscopic structure through the scattering from the ensembles of atoms in a sample. Neutron beams are much less intense than X-ray beams produced at large-scale facilities, and neutron crystallography requires larger samples than in analogous X-ray experiments. Nevertheless, neutron methods play a unique role in life and health sciences, due to the possibility of measurements in water, the natural media for life objects.

1.2. Current Challenges: To Soft and Life Matter. During the last decades the focus of modern research has shifted towards the study of soft matter with attempts to investigate life matter. Life matter is the most complicated and interesting subject for modern science. Really, this field of research is at the limits and in some cases even beyond the possibilities of present-day physics. Life systems have a number of specific features. They have long-living, slow-relaxing structures which are far from equilibrium. The next important property is irreversibility of many processes. We can explore some features of life matter such as kinetics, structure hierarchy, self-assembly by studying soft matter (Fig. 1). From my point of view, one of the main directions of the research programme for a new neutron source could be related to the study of soft and life matter and key problems of biophysics with application to biomedicine and pharmacology, which is in line with the modern trends in the world science. In this respect, we need the advanced development of all experimental techniques which are available now. Especially, it concerns small-angle neutron scattering (SANS) and reflectometry methods. The experimental complex at IBR-2 has only one SANS instrument. All three reflectometers do not operate at full capacity due to the on-going construction or reconstruction. This is a clear disadvantage in contrast to the situation in the leading neutron centers.

One recent example excellently demonstrates the potential of neutron technique. The challenge for structural biology in the 21st century is to develop a comprehensive description of protein structures, as well as complexes and assembles that they form to accomplish the essential functions of life: metabolism, mechanical movement, energy production and even thought process. The understanding of the molecules of life provides the foundations for treating diseases and developing new biotechnology applications.

Fig. 1. Current challenge: to soft and life matter



Crystalline Solids
Amorphous Solids
Quasicrystals
Low Dimension
Structures

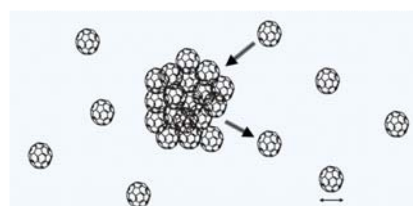
Solid Matter

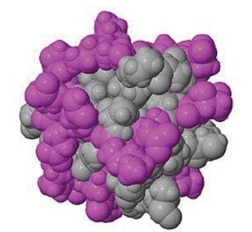
- fluctuations
- relaxation

- length scale intermediate between atomic size and macroscopic scales
- kinetics, self-assembly
- hierarchy

Soft Matter

neither simple liquids
nor crystalline solid





Life Matter

Nuclear Acids (DNA, RNA)
Proteins, Polysaccharides
Membranes

- long-living, slow-relaxing structures
- self-organization
- irreversibility

As was mentioned at the end of Subsec. 1.1, nowadays there are many advanced methods for condensed matter research. X-ray synchrotron radiation is very effective in structural biology, first of all, for crystalline samples. The problem is that only about 5% of proteins can be crystallized. Moreover, the central tenet of molecular biology states that the functions of a protein are fully determined by its folded three-dimensional structure, so that we have the system of a lock-and-key type. For example, an enzyme in the conventional view folds up immediately into a unique and stable 3D shape (the key). Its shape perfectly matches and allows it to bind its substrate (the lock). In the new view, protein segments can function when transiently or durably disordered [7]. Two cases are possible, which can be illustrated with the help of two proteins. A disordered part of the gene-regulatory protein CREB uses the lock to mould itself into the shape of the key when the two meet, rather than folding beforehand: fold as you bind. The signaling protein Sic1 remains disordered in its bound state, and each of six phosphate groups occupies the binding site in turn. The protein is a mix of different conformations shifting around in constant dynamic equilibrium: shape shifting.

Neutron scattering, combined with isotope (H, D) contrast variation, is posed to make major contributions in this area. It can elucidate the subtle structural relationships between molecular components in large protein complexes in solution, which is essential for unravelling how they behave. Variation contrast can be improved with the use of polarized neutrons. The application of isotope substitution and polarization analysis was performed in our papers [8] and demonstrated in Fig. 2.

Neutron scattering can be used not only for the determination of structures. A lot of basic problems of biophysics can be investigated at high-flux neutron sources, such as:

— coil-globule phase transitions, transformation of biopolymers and biological membranes to glassy states or liquid crystal states, etc.;

— intramolecular dynamics, dynamical regimes of a cell;

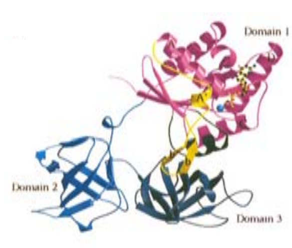
— ternary structure of biopolymers, etc.

From the general point of view, the most important investigations are related to dynamical and relaxation behavior, since life systems are strongly disequilibrium and biological processes have an irreversible character. These investigations are related to nonequilibrium statistical mechanics which is under intense development nowadays. This science is familiar for JINR due to the classical paper by N. N. Bogoliubov [9] and further investigations in the Bogoliubov Laboratory of Theoretical Physics [10]. See also [11].

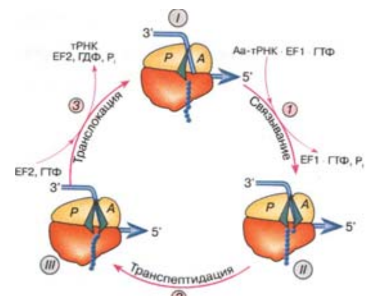
In this discussion I would like to mention two problems, which are beyond the scope of present-day physics [12]. The first one is a progressive biological evolution with the construction of more and more organized structures. JINR is

Fig. 2. Why do we need more neutrons: an example of an unstructured protein

Protein eEF1A – elongation factor of translation



Structure of elongation factor



Elongation cycle of the ribosome

Elementary elongation cycle of the ribosome, when one triplet (codon) of mRNA is read and one amino acid is added to the growing polypeptide.

The main role of elongation factors: to increase the rate of elongation and to facilitate accurate fixing of complexes.

Neutron scattering experiments with isotopic substitution and polarization analysis revealed that the eEF1A protein has no fixed rigid structure in solution, and its conformation is more expanded and disordered than its prokaryotic counterparts.

A fourth native state of eukaryotic factors (the state with high cross-domain mobility) was proposed.

I.Serdyuk, V.Aksenov et al. J.Mol.Biol. 292 (1999) 633; T.Budkevich, I.Serdyuk, V.Aksenov et al. Biochemistry, 41 (2002) 15342

related to this more-than-fundamental problem, since the Laboratory of Radiation Biology headed by E. A. Krasavin has begun its research activities based on classical works of N. V. Timofeev-Ressovsky and his disciple V. I. Korogodin. These investigations are being actively continued nowadays. An intense neutron source can provide wide possibilities for genetic investigations of different systems after irradiation.

The second problem is the origin of individual and general consciousness. This problem is related to a long-standing problem of quantum mechanics interpretation which has been discussed starting from the debates between N. Bohr and A. Einstein in the 1930s–1940s [13]. D. I. Blokhintsev also investigated this problem [14]. V. L. Ginzburg in his famous review on the problems of modern physics [15] emphasized three great challenges in physics [16]: quantum mechanics interpretation (what happens during quantum measurements?), arrow of time (where does irreversibility come from?) and consciousness and physics. Moreover, he related each of these problems to the others. Here, I will leave out the details. Still, we will consider the quantum measurement problem in the next section.

1.3. Fundamental Physics. The discovery of the Higgs boson opens a new era in physics. The established theory describing weak, strong and electromagnetic interactions of all known particles is the Standard Model (SM) of particle physics. However, it does not seem to be a complete theory. For instance, this model does not include gravitation. It cannot explain the existence of dark matter or dark energy. Currently, SM is able to describe less than 5% of the Universe's content. What is new physics beyond SM? Nowadays, there are many ideas about it and numerous experiments are currently being performed at huge particle accelerators. In this respect, precision experiments with low-energy neutrons can provide a great deal of new information. For example, the discovery of neutron-antineutron $(n\bar{n})$ oscillations could answer crucial questions of particle physics and cosmology [17]. Why do we observe more matter than antimatter in the Universe? Another related intriguing subject potentially accessible with this process concerns the mechanism responsible for neutrino mass generation. A high neutron flux combined with the progress made in neutron optics offers a remarkable opportunity to perform a sensitive experiment dedicated to search for such oscillations. The next flagship experiment could be direct measurement of neutron-neutron cross section. This experiment important for understanding of charge symmetry breaking in nuclear forces has not been realized so far. Since a pure neutron target does not exist in nature, the only way to perform such an experiment is to use an intense neutron source. FLNP has made many efforts to realize this experiment at pulsed reactors of the Federal Nuclear Centers [18]. This experience will be helpful for the future measurements.

To what I would like to draw your special attention is quantum mechanics and ultracold neutron (UCN) physics (see Fig. 3). Very intriguing perspectives open

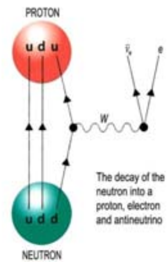
Fig. 3. Ultracold Neutrons (UCN) and New Physics

Ultracold neutrons (UCN)

Early Universe : τ_n
Baryon asymmetry : EDM
Dark matter and energy

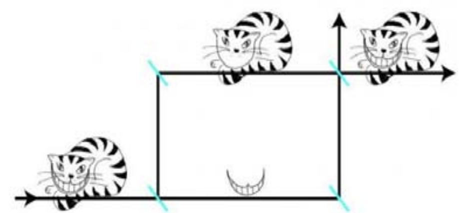
F.L.Shapiro

6.04.1915 – 30.01.1973

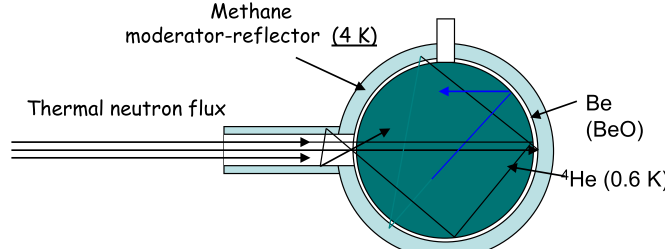


Surface and thin layer physics

Quantum measurements (a bridge between physics and consciousness problem)



Example: "Cheshire cats"
ILL polarized neutrons interferometer, 2014



Schematic view of the idea of the helium ultracold neutron source at thermal neutron source

E.V. Lychagin, A.Yu. Muzychka, G.V. Nekhaev, E.I. Sharapov, A.V. Strelkov (JINR, Dubna), V.V. Nesvizhevsky (ILL, Grenoble) up in experiments on the problem of quantum measurements. Nowadays, it is foreseen to be a bridge between quantum mechanics and consciousness problem. As an example, I refer to the experiment in ILL which was called "Cheshire cat" [19]. In this experiment the Cheshire cat is a neutron and its grin is the neutron spin component along the z-direction.

The extensive field of research is opened with the use of UCN. Traditional attempts are related to new physics beyond the SM through measurements of neutron lifetime τ_n and electric dipole moment (EDM). However, it seems that recent observations of UCN quantum states in a gravitational field have much prospect. Indeed, it is a new research field including the investigation of dark matter and dark energy, and especially precise measurements of structure and dynamics of surfaces at nanoscale.

UCN physics is traditional for FLNP. Remember that UCN were discovered by F. L. Shapiro's group in 1968. FLNP scientists take part in all leading experiments with UCN and have a number of new ideas for a new more intense neutron source.

1.4. Nuclear Physics. The understanding of the nucleus is an important field of research for intense neutron sources. Nuclei are collections of protons and neutrons. These can be plotted on a kind of nuclear landscape with a long valley of stability (Fig. 4). On either side of the valley of stability are areas inhabited by unstable nuclei with an increasing number of protons and neutrons. These areas are bounded by the so-called drip lines. It is known where the proton drip line is, but only the lower part of neutron drip line has been investigated so far. Studies of extreme nuclei provide stringent tests for nuclear models and also for the theories of underlying nuclear forces. Nuclei with high proton-to-neutron ratios can be obtained relatively straightforwardly with the help of accelerators. The obtaining of neutron-rich nuclei is more difficult, and only few facilities worldwide can produce their reasonable amounts.

One more line in the nuclear landscape must attract our attention, namely the r-process path or the rapid neutron capture process. The observational knowledge of the r-process is based on relative abundances of elements in the Sun and distant stars. The understanding of the path through which the heaviest elements are synthesized is a great challenge for nuclear physics.

You know that at the end of the last year the priority of the Flerov Laboratory of Nuclear Reactions for two elements 115 and 118 was acknowledged. Another column of the Mendeleev Table has been filled. But two fundamental questions arise: whether element 119 exists and what the properties of elements from the "stability island" are. We have a common research programme on element 119 initiated by Prof. Yu. Oganessian with the use of the PIK reactor. I believe that these investigations will continue for many years, so a new intense neutron source will be helpful in this research.

Fig. 4. Understanding the nucleus

Probing exotic (n-rich) nucleus

Nuclear Structure (nuclear models)

Phase Transitions in nuclei

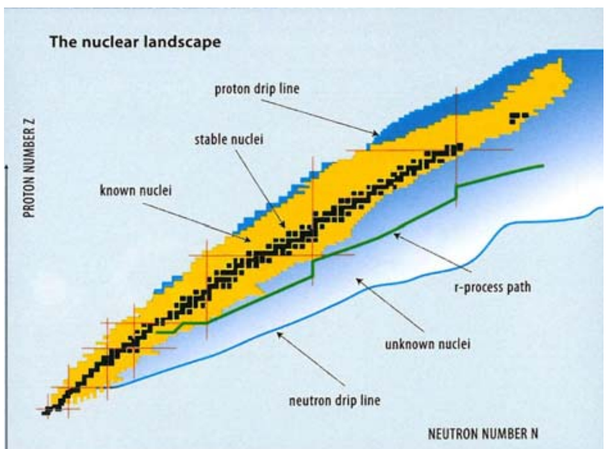
Fission Physics

Nuclear Data

Astrophysics (where do the heavy elements come from?)

Superheavy elements

Stability Island



2016:

113 – Nihonium (Nh),

115 – Moscovium (Mc),

117 – Tennessine (Ts),

118 – Oganesson (Og)

Neutron-rich nuclei located close to the r-process path can be created by nuclear fission. The fission itself is also a rich source of information: the abundances of the fission fragments produced and their excited states depend on the nuclear structure. A high-flux neutron source can provide very exotic neutron-rich nuclides with very high production yields. The pathway of the r-process can be determined by mass measurements for a set of these nuclides. The necessity to measure the masses of nuclides (total binding energies) brings us to the use of Penning traps for this purpose. In recent years, Penning traps have become very powerful and sensitive instruments for precise mass measurements [20]. The use of very sensitive trapping techniques (at the level of detecting a single ion) in combination with very high capacity of nuclide production by a high-flux neutron source will provide excellent conditions for investigations of very exotic nuclides including those to be discovered. Such an instrument can be considered as an astrophysical terrestrial laboratory.

There are a few Penning-trap facilities in the world which are actively used on-line at accelerators (ISOLTRAP/CERN, SHIPTRAP/GSI, JYFLTRAP/JYFL, TITAN/TRIUMF), and only one Penning trap is installed at a reactor — the TRIGA reactor in Mainz (TRIGATRAP). An instrument of this type is planned to be installed at the PIK reactor (PITRAP project [21]). Three areas of physics research are envisaged:

— investigations of fission products with a Penning trap installed either in the beam of a planned electromagnetic mass separator or in the beam of products delivered by a gas-jet system from an irradiated movable target;

— investigations of neutron capture products to study the astrophysical slow neutron capture process (s-process) with the predominant use of a gas target and/or accumulated long-lived products;

— off-line measurements of long-lived or quasi-stable nuclides for neutrino physics.

2. WORLD NEUTRON LANDSCAPE

A detailed analysis of the present state and development of neutron sources in the world has been given recently in our paper [22]. Here, I show (Table 1) only the world's leading pulsed sources as reference points. In Europe, there are only ten leading neutron centers with developed user system. Considering the present-day tendency, after 2030 only five sources will be available including three currently operating facilities: ISIS, SINQ (PSI, Villigen, Switzerland), FRM II (TU, Munich), and two new sources (ESS [23] and steady-state reactor PIK in the Petersburg Nuclear Physics Institute of the National Research Center "Kurchatov Institute" [24]) which are under construction at the moment. Over the last years this situation has caused active discussions on new neutron sources in Europe. A medium power source, which is much cheaper as compared to ESS, on the

Table 1. High-flux pulsed neutron sources for users

State, city	Name, start of operation/ refurbishment	Target power, MW	Neutron flux in pulse, 10^{14} cm$^{-2}\cdot$s^{-1}	Thermal neutron pulse duration, μs; frequency, s^{-1}	Averaged in time neutron flux, 10^{12} cm$^{-2}\cdot$s^{-1}	Number of beams/cold moderators	Experimental stations				
							Diffraction	Small angle	Reflectometer	Inelastic	Other
England	ISIS I, 1985	0.2	10	20–30; 50	1.5	16/2	10	2	3	7	1
Chilton	ISIS II, 2009	—	45	20–30; 5	0.7	13/1	6	4	5	2	2
USA											
Los Alamos	MLNSC, 1985	0.1	7	20–30; 20	0.4	16/2	4	2	3	2	2
Oak Ridge	SNS, 2006	1	12	20–50; 60	4	14/1	7	2	3	7	3
	STS, project	0.5	50	50–200, 10	10	—	—	—	—	—	—
Japan Ibaraki	JSNS, 2009, plan	1	20/65	20–50; 25	10/30	21/1	7	1	2	3	7
China Donguan	CSNS 2018, plan	0.1	~ 5	20–50, 25	~ 1	20	—	—	—	—	—
Russia Dubna	IBR-2, 1984/2012	2	60	310; 5	10	14/2	6	1	3	2	2
Sweden Lund	ESS, 2019, plan	5	50–75	2800; 14	200–300	16/1 first phase	5	2	2	6	1

basis of a deuteron linear accelerator with the Be target has been proposed recently [25] to be constructed at the Jülich Research Center. Similar sources for Saclay and Bilbao are under consideration.

To balance the world neutron landscape, one more intense pulse neutron source of the fourth generation is needed in Russia. For the advanced research programme outlined in Sec. 1, we need the following parameters for the neutron flux density: in pulse $\bar{\Phi} > 10^{16}$ cm$^{-2}\cdot$ s^{-1} and averaged in time $\bar{\Phi} > 10^{14}$ cm$^{-2}\cdot$ s^{-1}.

The PIK reactor will not be able to play this role. Like the IBR-2 reactor, the PIK reactor belongs to the third generation of neutron sources. The project was proposed in the late 1960s, the construction was started in 1976. After the Chernobyl disaster the project was reconsidered to comply with new safety rules. Since 1992, the state financial support was really stopped and the construction was frozen till 2007 when the restart of works led to the physical startup in 2011, when PNPI was included in the NRC "Kurchatov Institute". The civil construction was finished in 2013; the power startup is scheduled for 2018 and first 12 instruments for experiments — for 2019. According to the project, the PIK reactor will have 100 MW power, $5 \cdot 10^{15}$ cm$^{-2}\cdot$ s^{-1} in the central channel of the core and $(1{-}2) \cdot 10^{15}$ cm$^{-2}\cdot$ s^{-1} on the moderator surface, which is comparable to the parameters of the HFR reactor of the Institut Laue–Langevin.

The pulsed neutron sources discussed above are used mainly for neutron scattering, as we can see in Table 1. Remember that neutron sources for beam

Table 2. Very short pulsed neutron sources for nuclear physics

Neutron source (laboratory)	$\langle I_n \rangle$, 10^{15} s^{-1}	Δt, ns	Q, 10^{30} s^{-3}	Number of instruments for nuclear physics experiments
LANSCE (LANL, USA)	10	1–125	0.64*	8 (total, partial cross sections) + ICE House test facility
n_TOF (CERN, Switzerland)	0.4	10	4	6 (total, capture, fission, scattering, (n, α))
ORELA (ORNL, USA)	0.13	2–30	0.14*	5 (total, partial cross sections)
GELENA (IRMM, Belgium)	0.025	1	25	5 (total, partial cross sections)
GNEIS (PNPI, Gatchina)	0.3	10	3	3 (total, capture, fission) + ISNP/GNEIS test facility
IREN (JINR, Dubna, project)	1.0	400	0.0062	Under construction

$\langle I_n \rangle$ — average intensity of neutrons emitted in 4π solid angle; Δt — neutron pulse width; $Q = \langle I_n \rangle / (\Delta t)^2$ — quality coefficient of the neutron source; * — present value corresponds to maximum pulse width.

research can be either steady-state (mostly reactors) or pulsed (mostly accelerators). The latter sources vary in pulse duration: $\Delta t < 10$ μs (very short pulse), $10 < \Delta t < 50$ μs (short pulse), $\Delta t > 300$ μs (long pulse). For the traditional neutron spectroscopy in nuclear physics where resonance neutrons are used, for the most part, very short pulses are needed (see Table 2). For neutron spectroscopy in condensed matter where thermal neutrons are used predominantly short pulses are needed. After the successful experience of the IBR-2 reactor ($\Delta t = 320$ μs) the attention of neutron society was drawn to long-pulse sources (LPS). ESS, for example, has $\Delta t = 2800$ μs. The main advantage of LPS is high neutron flux and, as a result, a possibility to perform not only scattering experiments on condensed matter but also experiments on fundamental physics and nuclear physics as was discussed in Subsecs. 1.3. and 1.4. We can conclude that a new neutron source will be especially high in demand being a long pulse source. For JINR with its IBR-2 experience the pulse duration in the interval $100-300$ μs would be most suitable. It would also be highly preferable to have two or three target-moderator stations for thermal and cold neutrons. In this case all possibilities of neutrons can be used. This variant will be discussed in the next section.

3. DUBNA NEUTRON SOURCE OF FOURTH GENERATION (DNS-IV)

We consider ESS as the main reference point with the goal to have similar parameters of the source and its cost as low as possible. For this reason we consider subcritical reactor systems driven by either mechanical reactivity modulation (pulsed reactor) or proton accelerator (booster). In the latter case the subcritical reactor plays the role of a neutron multiplying target. The multiplying coefficient can be rather high, up to several tens (up to 100), which compensates for the accelerator power and makes the facility cheaper.

Our calculations [26] of the upper limit parameters of pulsed sources with the use of the fission reaction for several configurations lead to the value of $\bar{\Phi} = (1-2) \cdot 10^{14}$ cm$^{-2}\cdot$ s^{-1}. For the variants with the proton accelerator the following parameters are acceptable: mean proton current $\bar{j} \approx 0.1$ mA, energy $E_p \approx 1$ GeV, proton pulse duration 100–200 μs, pulse frequency $\nu = 10$ s^{-1}. The conclusion is that it is possible to construct a pulsed source with parameters close to parameters of ESS but at a significantly lower cost.

The following variants of the DNS-IV concept are considered in FLNP.

I. Pulsed reactor NEPTUN

Pulsed reactor NEPTUN [27] is a pulsed reactor of a new (different from IBR-2) design with neptunium-based fuel.

II. Subcritical multiplying target at NICA booster system (NEPTUN or COBRA)

NICA (Nuclotron-based Ion Collider fAcility) is a new accelerator complex designed at the Veksler and Baldin Laboratory of High Energy Physics to study properties of dense baryonic matter [29]. As I was informed, a new superconducting proton synchrotron in complex of nuclotron will be built in 2–3 years, with parameter suitable for our project. We are considering the possibility of creating target stations at this proton synchrotron (see Fig. 5). VBLHEP, as well as FLNP, has many years of experience with accelerator-driven subcritical systems.

II.1. Pulsed reactor NEPTUN [27] in two modes:

(1) without reactivity modulation (booster); reactor core plays the role of multiplier of neutrons produced by spallation target;

(2) pulsed reactor driven by proton accelerator (superbooster).

II.2. Booster COBRA (Cascade Booster RAzmnozhitel) [28] is a cascade multiplying target of plutonium or neptunium (Fig. 5).

Variants I and II lead to practically equal parameters, one order higher than those of IBR-2 and at a very similar cost: 100–150 MEUR.

III. Dubna Advanced Neutron Source (DANS)

DANS is proposed to be based on a new linear superconducting proton accelerator (see, for example, [30]) with several target stations. The idea of three target stations was suggested in the initial project of ESS: long pulse stations, short pulse station with an additional accelerator — accumulator and UCN station. Nowadays only one target station (LPSD) is under development. For implementation of the research programme outlined in Sec. 1, the facility layout proposed for the new medium flux source (HBS) by Jülich Research Center [25] is more appropriate. The basis of this facility is a target-moderator combination that offers a pulsed neutron beam at an optimal frequency, pulse duration and neutron spectrum to meet the requirements of the instruments oriented at solving specific scientific problems.

The design of DANS should be based on a specialized proton accelerator with optimized energy and current that is multiplexed to feed several target stations (multiplying subcritical reactors, one from variants II) operating at different frequencies. Three possible target stations are under consideration: for thermal, cold and ultracold neutrons.

DANS can be realized as a neutron factory to fulfill a wide spectrum research programme. Thermal neutrons can be used for high resolution and real-time diffraction and spectroscopy of atomic structures, cold neutrons — for small-angle scattering and reflectometry for large-scale structures including soft and biomatter, ultracold neutrons — for fundamental physics and precise elastic and inelastic surface reflections as a probe for nanostructured materials.

Figure 6 summarizes the parameters of DNS-IV in comparison with those of the world's leading neutron sources. Here we used the picture of ESS and added our data (red).

Fig. 5. Cascade Booster RAzmnozhitel

COBRA

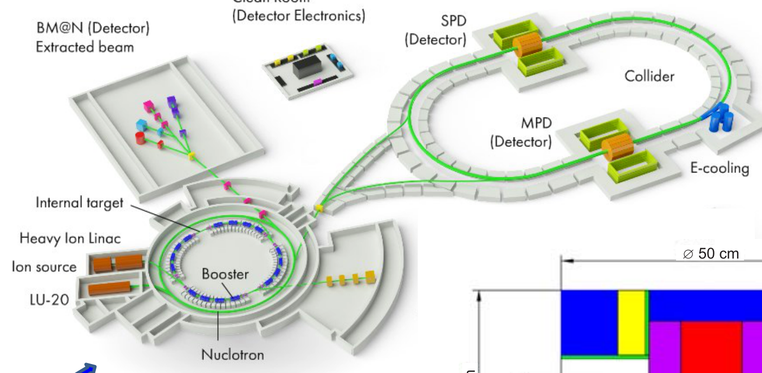
proton superconducting synchrotron (Booster)

$E_p \geq 0.8$ GeV

$\hat{I} \geq 0.1$ mA, $\nu = 10$ s^{-1}, $\Delta t_p = 100 - 200$ μs

neutron generating target + subcritical assembly

NICA Complex



Target Station

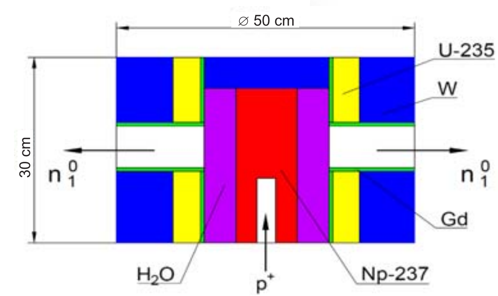


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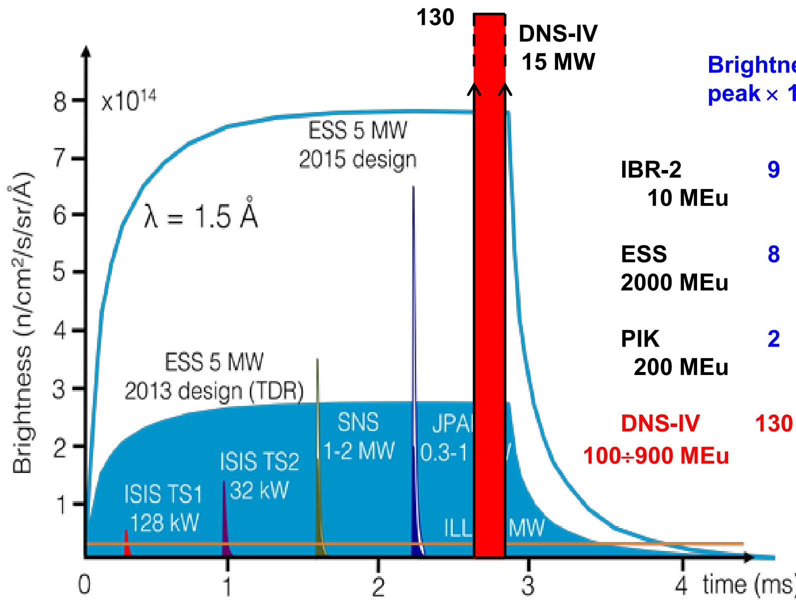
Fig. 6. Dubna Neutron Source of fourth generation (DNS-IV) vs. other sources



	Brightness, peak × 10^{14}	Flux density, time aver.	Flux density, peak
IBR-2 10 MEu	9	0.1	58
ESS 2000 MEu	8	2	75
PIK 200 MEu	2	10	10
DNS-IV 100÷900 MEu	130	3	800

Data $\times 10^{14}\ [n \cdot cm^{-2} \cdot s^{-1}]$

Single-pulse source brightness as a function of time at wavelength of 1.5 A at ESS, ILL, SNS, J-PARC and ISIS Target Stations 1 and 2. In each case, the thermal moderator with the highest peak brightness is shown. (Source: ESS)

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CONCLUSIONS

1. The use of neutrons in modern sciences is growing due to their unique properties. In general, the research programme at the IBR-2 reactor is in line with the current trends. We should pay more attention to research of soft and life matter to keep abreast of challenges in modern science.

2. The number of neutron sources in the world is decreasing in contrast to the increasing demand for them. This situation has arisen because of the ongoing decommissioning of old sources, mostly reactors, which are over 40 years old. To balance the European neutron landscape, a new intense neutron source of the fourth generation is required on the territory of Russia. And Dubna is the most appropriate place due to the long-term development of neutron research here. This source will be complementary to ESS and the PIK reactor.

3. A number of flagship experiments are proposed for an intense neutron source of the fourth generation for condensed matter research (including molecular biology), fundamental and nuclear physics.

4. We have shown [26] that it is possible to construct a pulsed neutron source on the basis of fission reaction with the parameters similar to those of ESS but at least twice cheaper. To proceed further with the concept detalization and start of the project research and development, we need to concretize the source parameters for the advanced research programme. In FLNP, two working groups (on nuclear physics and on condensed matter research) have been organized. In parallel, we will continue the investigations of the ideas proposed in [27, 28] which cover more detailed consideration of an accelerator and target-moderator systems.

5. An optimistic road map can be represented as follows: conceptual research — 2016–2017; technical study — 2018–2020, research and development phase — 2021–2023, engineering design — 2024–2026, construction phase — 2027–2032, commissioning — 2032–2035.

6. A new neutron source based on a proton accelerator (probably booster of NICA complex) will give new possibilities in both fundamental and applied research including neutron activation analysis for ecology, pharmacology and biomedicine; muon physics including muon spectroscopy; radiation physics and radiation biology, isotope production, etc. Without any doubt, this facility will give new prospects for all JINR Laboratories.

Thank you for your attention!

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