Pulsed reactors for neutron studies of matter

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The present status and the prospects for the development of pulsed reactors as neutron sources for physical investigations of nuclei and condensed matter are considered. Their advantages and disadvantages in comparison with other neutron sources are discussed. © *1995 American Institute of Physics.*

INTRODUCTION

In modern physics, neutrons are used to study fundamental interactions (neutron lifetime, violation of spatial parity and of time-reversal symmetry) and nuclear structure, but they are also more widely used in the physics of condensed media, biology, chemistry, material science, and nondestructive monitoring of industrial plants.

One can identify the following major divisions in these fields: crystallography, magnetism, fluids, including superfluids, and amorphous bodies, surfaces and layered systems, biological membranes, proteins, chemical reactions, polymers, aging of materials, element analysis, internal stresses, and texture. It must be emphasized that most of these studies are aimed at the investigation of not merely the properties of new materials, although this is important, but rather new physical effects, with which the physics of condensed media is continually equipping natural science. One of the recent examples of the decisive role of neutrons in the study of a new physical effect is the unraveling of the structure of high-temperature superconductors.

The possibilities of studies with neutrons are extended by the existence of more intense sources. This comes about not only because of the increase in the speed with which the experiments can be made but also in the opening up of new possibilities, among which one may include an increase in the accuracy of measurements, the possibility of studying small objects, the possibility of studying complicated objects and objects with small scattering cross sections, and the performing of experiments with analysis of the neutron polarization before and after scattering. The desire of the neutron community to have more intense neutron sources is therefore natural.

The main intense neutron sources for physical investigations are still nuclear reactors with a continuous flux, although in the fifties the use of accelerators for these purposes was proposed.[1] The first nuclear reactor was built under the leadership of Fermi in 1942 in Chicago (USA), and intense pulsed neutron sources based on electron accelerators began to be built at Harwell (Great Britain) in the fifties.[2]

There are no decisive advantages of reactors over accelerators, but the gap of ten years and the rapid development of reactor technology during that same time determined the development of the basis for neutron studies.

Since the beginning of the nineties, the number of reactors has steadily decreased, and at the beginning of the next century it may reach the level of the sixties. At the same time, during the last 30 years great progress has been observed in accelerator technology, which has great prospects. It is therefore obvious that the next stage in the development of intense neutron sources is associated with the use of accelerators, mainly proton accelerators.

In contrast to reactors with a continuous flux, sources based on accelerators generally emit neutrons in pulses, and this calls for the use of different experimental methods—time-of-flight methods. Time-of-flight methods already began to be used in the first years of the development of neutron investigations in nuclear physics. However, for this it was necessary to use choppers in the neutron reactor beams, and this greatly reduced their efficiency. To avoid this, physicists at the Physics and Power Institute (Obninsk, Russia) under the leadership of D. I. Blokhintsev proposed a new type of nuclear reactor—a periodic pulsed reactor,[3,4] which generated neutrons in pulses with the frequency needed to perform experiments. The first such reactor was commissioned at the Joint Institute for Nuclear Research on June 23, 1960 (Ref. 5).

In parallel with the construction of the reactor at the Laboratory of Neutron Physics, a physics program was prepared under the direction of I. M. Frank and F. L. Shapiro.[6] The results of the first experiments were published[5] in 1961 simultaneously with the publication of results obtained using the electron accelerator "General Atomic" (USA).[7]

Thus, 35 years ago Dubna became the birthplace of a new direction in the creation of neutron sources for physical studies and one of the creators of the time-of-flight methods using neutron scattering in the physics of condensed media. Were the pulsed reactors effective? What position do they occupy among other types of sources? What are the prospects for their development? The aim of this paper is to attempt to answer these questions.

METHODS OF OBTAINING NEUTRONS

Historically, the first intense neutron sources were nuclear reactors, in which a constant neutron flux was generated in the process of spontaneous fission of uranium. Constant-flux nuclear reactors have limits on the neutron flux that can be achieved, these being due to technological factors that are mainly associated with the extraction of heat. In this sense, definite possibilities are opened up for periodic pulsed reactors, in which modulation of the reactivity raises the yield of neutrons that are useful for beam investigations by a factor of hundreds for the same mean power.

In the following type of source, the photonuclear reaction and linear electron accelerators are used. Since in the photonuclear reaction the neutron yield is low—1 neutron per 20 electrons with energy 100 MeV—to raise the neutron yield it was found to be effective to use a multiplying target (booster) and multiplying target with reactivity modulation (superbooster), for the development of which experience from operating a periodic pulsed reactor was used.

From the point of view of neutron production, the most productive reaction is evaporation using a proton synchrotron, which gives ~30 neutrons for 1 proton with energy ~800 MeV. The use of multiplying targets can increase the neutron yield by a further factor of about 20.

The modern tendency in the development of intense neutron sources is oriented toward sources of evaporation type. However, the development of reactor sources is still topical for a number of reasons. First, proton synchrotrons with the necessary parameters are rather complicated and expensive machines. Second, the practical realization of high-power target devices comes up against typical reactor problems such as heat extraction and the radiation resistance of the construction, which is determined by the flux density of the fast neutrons in the spectrum of the core or target. Finally, at the present time there are still quite a large number of operating reactors that have prospects for development.

Research nuclear reactors as neutron sources became widespread from the end of the fifties. To a large degree, this was helped by the work of the International Atomic Energy Agency, which was set up by the United Nations in 1957. The IAEA did much propaganda work in support of the use of natural uranium for the production of nuclear fuel, the building of nuclear reactors, the organization of their safe operation, and also the production of isotopes for use in medicine, agriculture, industry, and for other purposes. As a result, in the sixties every industrially developed country had or tried to have nuclear reactors, since this was an indicator of economic power.

Besides radiation studies and the production of isotopes, nuclear reactors were used from the beginning for physical studies with extracted neutron beams. These studies proved to be so informative and important for problems of nuclear physics and the physics of condensed media that from the middle of the sixties neutron sources that were specially optimized for beam studies began to be built.

The building of the greatest number of reactors occurred in the period from 1955 to 1960. These were the first-generation reactors, which were built for irradiation purposes and for radiation studies. After 1960, the building of second-generation reactors began; these were already intended for both radiation studies and studies using neutron beams. The first continuous-flux reactor of the third generation, i.e., a reactor intended for beam studies, was built in 1965 at Brookhaven, five years after the construction of the pulsed reactor IBR, which from the very beginning was intended solely for beam studies. Up to about 1960, the increase in the neutron flux had matched the increase in the power of the reactors, but later the further increase of the neutron flux began to move ahead of the increase of the reactor power. This development began to be manifested especially from the beginning of the seventies, when effective use began to be made of third-generation reactors such as HFR at ILL (Grenoble, France), ORPHEE at LLB (Saclay, France), IR-8 at the Russian Scientific Center "Kurchatov Institute" (Moscow, Russia), IBR-2 at the Laboratory of Neutron Physics of the JINR (Dubna, Russia), and others.

At the present time, there are about 50 research reactors in the world used to carry out beam studies. At the same time, most of them are reactors that have already been working for more than 30 years, a duration that is close to the natural lifetime of a reactor, since most reactors need to be modernized or replaced by new ones.

Ultimately, the efficiency of operation of a reactor is determined by the operation of the experimental facilities. Table I gives examples of reactors of the third generation and, partly, the second designed mainly for beam studies.[8] In accordance with the widely accepted classification, the measuring devices are divided into five types: diffractometers for elastic and diffuse elastic scattering, devices for small-angle scattering, reflectometers, spectrometers for inelastic and backward scattering, and special devices. These last devices include everything that is not included in the previous four categories. Facilities for irradiation and activation analysis are not considered here.

As can be seen from Table I, the most efficient reactors on the basis of all indicators are the reactor HFR among the high-power reactors and the reactor ORPHEE among those of intermediate power. The reactor HFR has the greatest absolute and specific (relative to the power) neutron flux and the most highly developed infrastructure for performing experiments. The organization of the work at the ILL can serve as a good example of international collaboration. We may mention in passing that one of the main reasons for the success of the ILL is that in this Institute the measuring instruments are renewed every 10–12 years; although this is very expensive, it does ensure a high level of the investigations. The reactor ORPHEE, like the reactor IR-8, is evidently optimal for the reactors of intermediate power and can serve as a good example of the organization of the work of a national center.

Besides the technological parameters, a very important factor is the cost. To a large degree, the cost of a reactor is determined by its mean power, and therefore a nominal parameter that determines the cost of a produced neutron can be taken to be the ratio of the mean power to the flux density. The greater the number of experimental facilities at a reactor, the more efficient is its use. One can say that each produced neutron is correspondingly cheaper. If we use the data of Table II, we see that among all the reactors HFR at ILL and ORPHEE at LLB are distinguished. By virtue of its low mean power, the reactor IBR-2 significantly exceeds all reactors, but since it is a pulsed source, it requires separate consideration.

Considering the overall situation, we see that despite the strong development in recent years of means for achieving more efficient reactor use—moderators, neutron-guide systems, and modern spectrometers—the number of modern reactors available for physical research in the world is clearly inadequate to meet all the increasing requirements of physi-

TABLE I. High-flux research reactors and instruments used for scattering experiments.

Country	Reactor	Location	Year of construction	Power, MW	Flux$\times 10^{14}$, neutron $\cdot cm^{-2} \cdot s^{-1}$	Neutron channels	Moderators C: cold H: hot	Instruments for neutron scattering: Diffractometer	Small-angle neutron scattering	Reflectometer	Inelastic scattering	Special instruments	Total number
Canada	NRU	Chalk River	1957	125	3	6	C	3	1	0	2	0	6
Denmark	DR-3	Riso	1960	10	1.5	4	C	1	1	0	5	0	7
France	SILOE	Grenoble	1962/87	35	4	3	C	4	0	0	2	0	6
France	HFR-ILL	Grenoble	1971/95	58	15	26	2C,H	11	2	0	10	2	25
France	ORPHEE	Saclay	1980	14	2.5	20	2C,H	10	4	1	7	0	22
Germany	FRJ-2	Jülich	1962/72	23	2	8	C	4	3	1	7	3	18
Germany	BER-II	Berlin	1973/91	10	1	9	C	6	1	1	5	1	14
Hungary	WWR	Budapest	1992	10	1	8	-	2	1	1	3	3	10
India	Dhruva	Bombay	1985	100	2	13	C	3	1	0	8	1	13
Japan	JRR-3M	Ibaraki	1990	20	2	26	C	4	1	0	10	5	20
Holland	HFR	Petten	1961/70	45	1	12	-	3	1	0	2	1	7
Russia	BBP-M	Gatchina	1959	16	1	14	-	3	2	0	1	6	12
Russia	IR-8	Moscow	1981	8	1	12	C	2	0	0	3	5	10
Russia	IVV-2M	Ekaterinburg	1966/83	15	2	6	-	4	1	0	1	0	6
Russia	IBR-2 (pulsed)	Dubna	1984	2/1500	0.1/100	14	C	6	1	2	4	1	14
Sweden	R-2	Studsvik	1960	50	4	8	C	6	0	0	2	0	8
USA	HFBR	Brookhaven	1965	60	9	9	C	3	3	1	6	2	15
USA	HFIR	Oak Ridge	1966	100	30	4	-	4	1	0	5	0	10
USA	MURR	Missouri	1966	10	1.2	6	-	3	2	1	2	6	14
USA	NBSR	Gatesburg	1969	20	4	5	C	2	0	0	6	1	9

cists, biologists, chemists, and material scientists.

PULSED REACTORS

The history of pulsed reactors began in 1945, at the time of the Manhattan project. Three types of pulsed reactors can be distinguished (Ref. 9): aperiodic (self-extinguishing) pulsed reactors, periodic pulsed reactors, and boosters.

The most widely used reactors are those of the first type, mainly for radiation studies because of the huge peak flux that is possible. Because the pulses are aperiodic and, consequently, the mean flux is low, such reactors are seldom used in systematic beam investigations. As an example of the use of an ultrapowerful reactor of this type, we may mention the experiment that is being prepared to measure the neutron lifetime in a facility for ultracold neutrons with record density up to 10^4 neutron/cm^3 in the BIGR reactor at the research institute at Arzamas-16 in Russia. For comparison, the flux density for the ILL source reached 10^2 neutron/cm^3. The facility is being created by a group from the I. M. Frank

TABLE II. Basic parameters for neutron scattering experiments with the IBR-2 reactor.

Forms of scattering, research directions	Resolution of spectrometers	Mean neutron flux on sample
Elastic High-precision analysis of the structure of polycrystals and single crystals. Changes of structure induced by temperature, external pressure, and electric and magnetic fields	$\Delta d/d$ to 10^{-3}, diffractometers FDVR, DN-2, DN-12, SNIM-2, NSVR	Up to 10^7 neutron/cm^2/s, range of neutron wavelengths λ from 0.8 to 20 Å
Small-angle Structures above atomic scale, from 10 to 300 Å	Spectrometer YuMO, $\Delta Q/Q$ to $4\cdot 10^{-2}$	Up to $4\cdot 10^7$ neutron/cm^2/s, range of λ from 0.7 to 17 Å
Inelastic Dynamics of crystals, polymorphic materials, classical and quantum liquids	Spectrometers NERA, KDSOG-M, DIN-2PI, DIN-2PI, $\Delta E/E$ to 10^{-2}	Up to $7\cdot 10^6$ neutron/cm^2/s, interval of energy transfers from 0 to 300 MeV
Reflection from surfaces Surfaces of magnetic and nonmagnetic films, phase interfaces	Reflectometers SPN-1, REFLEKS-1, REFLEKS-2, $\Delta\theta/\theta \leqslant 3\cdot 10^{-2}$, beam polarization up to 96%	Up to 10^6 neutron/cm^2/s, range of λ from 0.7 to 10 Å

Laboratory of Neutron Physics in conjunction with physicists at Arzamas-16.

Reactors of the TRIGA type were widely adopted. These have a high, practically instantaneous negative temperature coefficient, and they therefore have a high degree of safety. The first reactor of this type, TRIGA I, began operation in 1958 in the United States; at the present time, there are 65 such reactors in the world, and they are mainly used in the regime of continuous operation, and also for teaching purposes.

The idea of a periodic pulsed reactor was proposed[3,4] in 1955. The construction of the reactor was begun in 1957 at Dubna under D. I. Blokhintsev, and it was commissioned on June 23, 1960 with mean power 1 kW (Refs. 5 and 6). This was the first reactor in the world in which pulses were generated periodically, with frequencies 5 and 50 Hz, by rotation of part of the core. In 1969, the power of the reactor was raised to 25 kW. It was given the name IBR-30. In it, the moving part of the core was divided into two parts to reduce the thermal load. Since 1986, the IBR-30 has been operating as a photonuclear source with multiplying target (booster) with mean power 10 kW and a yield of neutrons in a pulse that lasts 4 μs. Its further development will be considered in the following section.

The successful operation of the IBR reactor and its modifications stimulated further development of this direction. Several new projects were advanced in the middle of the sixties. The first proposal[10] was for the pulsating reactor SORA with moving reflector and mean power 1 MW. It was planned to construct the reactor at the Euratom Research Center at Ispra in Italy. It was planned to build a powerful periodic pulsed reactor with mean power up to 30 MW at the Brookhaven National Laboratory in the United States.[11] In 1964, work began at Dubna on the project of a new reactor IBR-2. The basic difference between IBR-2 and the series of IBR reactors was modulation of the reactivity by a moving reflector, and also cooling of the core by liquid sodium.[12] Among all the proposals for new powerful pulsed reactors, only the IBR-2 project was realized. This was made possible by the experience of operation with such systems at Dubna and Obninsk and also the support of the Ministry of Intermediate Mechanical Engineering of the USSR.

Officially, work on the IBR-2 project began in 1966, and the construction work was begun in 1969. The first critical assembly was made in the Physics and Power Institute, Obninsk in 1968, and during the period from 1970 through 1975 a model of the moving reflector was tested in Dubna. The reactor was started up physically (without coolant) eight years after the start of construction, at the end of 1977 and beginning of 1978. Work then began on the preparation for operation with power output (with sodium coolant), and this was effectively completed on April 9, 1982 with the achievement of a mean power of 2 MW at pulse frequency 25 Hz and the performing of the first physical experiments using extracted beams. Officially, the reactor was commissioned for use on February 10, 1984, and a program of physical experiments was begun on April 9, 1984 after a power of 2 MW had been achieved at pulse frequency 5 Hz. It can be seen from this account that the time required to master the operation of the reactor was nearly the same as the time required for its actual construction. This can evidently be explained by the novelty and unusual nature of the task to be performed.

Figure 1 shows a photograph of the building of the IBR-2 reactor and the IBR-30, while Fig. 2 is a photograph of the reactor hall of the IBR-2.

A schematic diagram of the IBR-2 is shown in Fig. 3. The reactor core has a volume of 22 liters and contains 82 kg of plutonium dioxide. The reactivity is modulated by a moving steel reflector, which consists of two parts that rotate at different rates (1500 and 300 rev/min) (Fig. 4). When both parts of the reflector pass through the core, a pulse of power 1500 MW is generated. For a regular regime of operation of the reactor—2500 hours per year on experiments—the core can be used without fuel replacement for not less than 20 years, and the time for which the moving reflector can be used is 5–7 yr. On March 27, 1995, the IBR-2 began to operate with a new (the third) moving reflector (Fig. 5), which is expected to last for 7 yr. In seven years' time, in 2002, it will also be necessary to replace the core.

Thus, the IBR-2 is a very cheap and economic reactor and, as the experience of more than ten years of operation has shown, it is a machine that is simple and safe in exploitation. The construction of the IBR-2 cost about 20 million roubles (in 1984 prices). At the present time, the use of the reactor, including the program of its development and salaries of all the servicing personnel, costs just over 1 million US dollars per year. At the same time, the reactor gives a neutron flux in a pulse of 10^{16} neutrons/cm^2·s, which is a record for research sources.

During the time that the IBR reactor has been operated, a complex of spectrometers has been set up around it, and the complete facility makes it possible to carry out investigations at a modern level with neutron scattering in all topical problems of the physics of condensed media, chemistry, biology, and material science. Figure 6 shows the general arrangement of the experimental hall of the reactor. More detailed information about the parameters and possibilities of the spectrometers is given in the publications of Refs. 13 and 14, in the booklets for users, and in the annual reports of the I. M. Frank Laboratory of Neutron Physics.

Although it holds the record in the world for the flux of thermal neutrons in a pulse, the IBR-2 reactor does not match the evaporation neutron sources in the pulse width (300 μs compared with 10–13 μs), and this is often noted as a shortcoming of the periodic reactor, since this parameter of the source affects the resolution of the measuring devices. This important question requires special consideration.

In neutron scattering experiments, one measures the double differential cross section for scattering into an element of solid angle $d\Omega$:

$$\frac{d^2\sigma}{d\omega d\Omega}=\frac{k_1}{k_0}S(Q,\omega),$$

where $\mathbf{k}_0$ and $\mathbf{k}_1$ are the wave vectors of the incident and scattered neutron, $\hbar\omega=(\hbar^2/2m)(k_0^2-k_1^2)$ is the energy transfer, and $\mathbf{Q}=\mathbf{k}_0-\mathbf{k}_1$ is the scattering vector. The wave vector is related to the neutron wavelength by $|\mathbf{k}|=k=2\pi/\lambda$. If

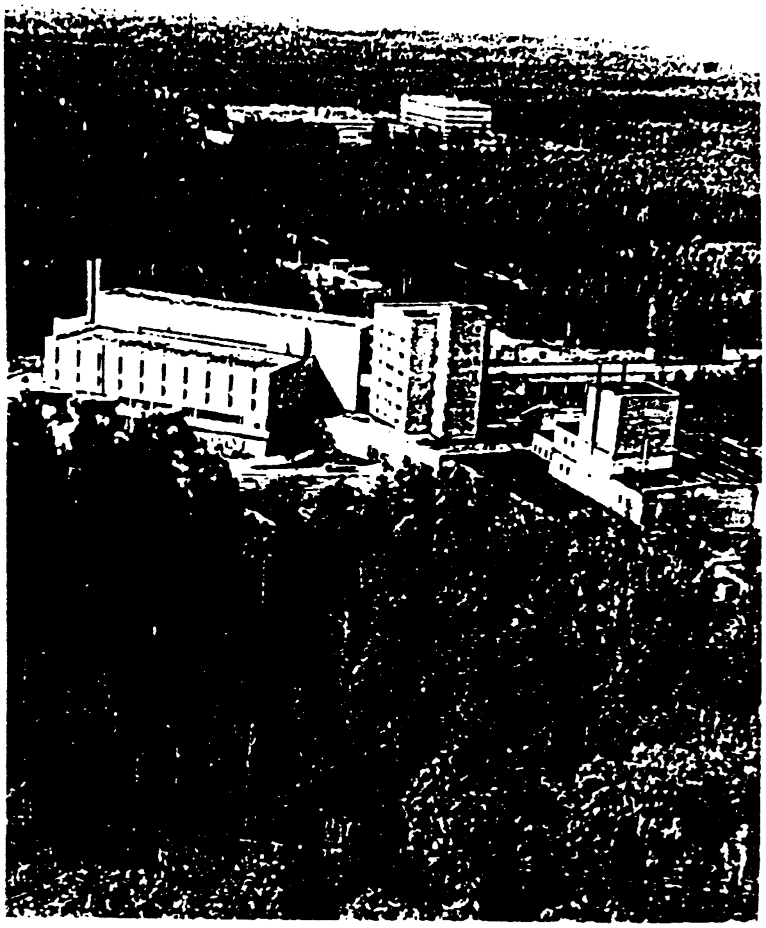

FIG. 1. General form of the buildings of the IBR-30 facility and the IBR-2 reactor.

pulsed neutron sources are used, one measures the time-of-flight t over the distance L_0 from the source to the sample and from the sample to the detector, L_1; here, the relation $\lambda h/mv=0.4/v=0.4t/L$ is used. All information about the properties of the sample is contained in the scattering function $S(Q,\omega)$.

The accuracy of the measurements (the resolution of the instruments) depends on the accuracy with which the energy and momentum transfers are measured, and this accuracy, in its turn, depends on the type of experiment. According to the type of instruments and the nature of the information that is obtained, four main types of neutron scattering experiment are distinguished: diffraction, small-angle scattering, reflection from a surface, and inelastic scattering. In each of these experiments, the accuracy of the measurement is determined by different dependences.[15] Moreover, it must be borne in mind that the above classification is very crude, and within each type there are many different ways in which an experiment can be arranged. We give below the dependences of the accuracy of the measurement for the different types of experiment; these are to be taken merely as qualitative and illustrative.

Diffraction:

$$\frac{\Delta Q}{Q}\approx\left[\left(\frac{\Delta t_m}{t}\right)^2+\frac{\Delta L}{L}+(\cot\,\theta\Delta\theta)^2\right]^{1/2}, \tag{1}$$

where Δt_m is the time half-width of the neutron pulse after the moderator, and θ is the scattering angle.

Small-angle scattering:

$$\frac{\Delta Q}{Q}=\left[\left(\frac{\Delta\theta}{\theta}\right)^2+\frac{\delta_m^2}{(L_0+L_1)^2}\right]^{1/2}, \tag{2}$$

where δ_m is the effective distance.

Reflectometry:

$$\frac{\Delta Q}{Q}\approx\cot\,\theta\Delta\theta\approx\frac{\Delta\theta}{\theta}. \tag{3}$$

Inelastic scattering in inverted geometry:

$$\frac{\Delta\hbar\omega}{E_0}\approx2\left[\left(\frac{\Delta t_m}{t}\right)^2+\left[\frac{E_1}{E_0}\cot\,\theta\Delta\theta\left(1+\frac{L_1}{L_0}\left(\frac{E_0}{E_1}\right)^{3/2}\right)\right]^2\right]^{1/2}. \tag{4}$$

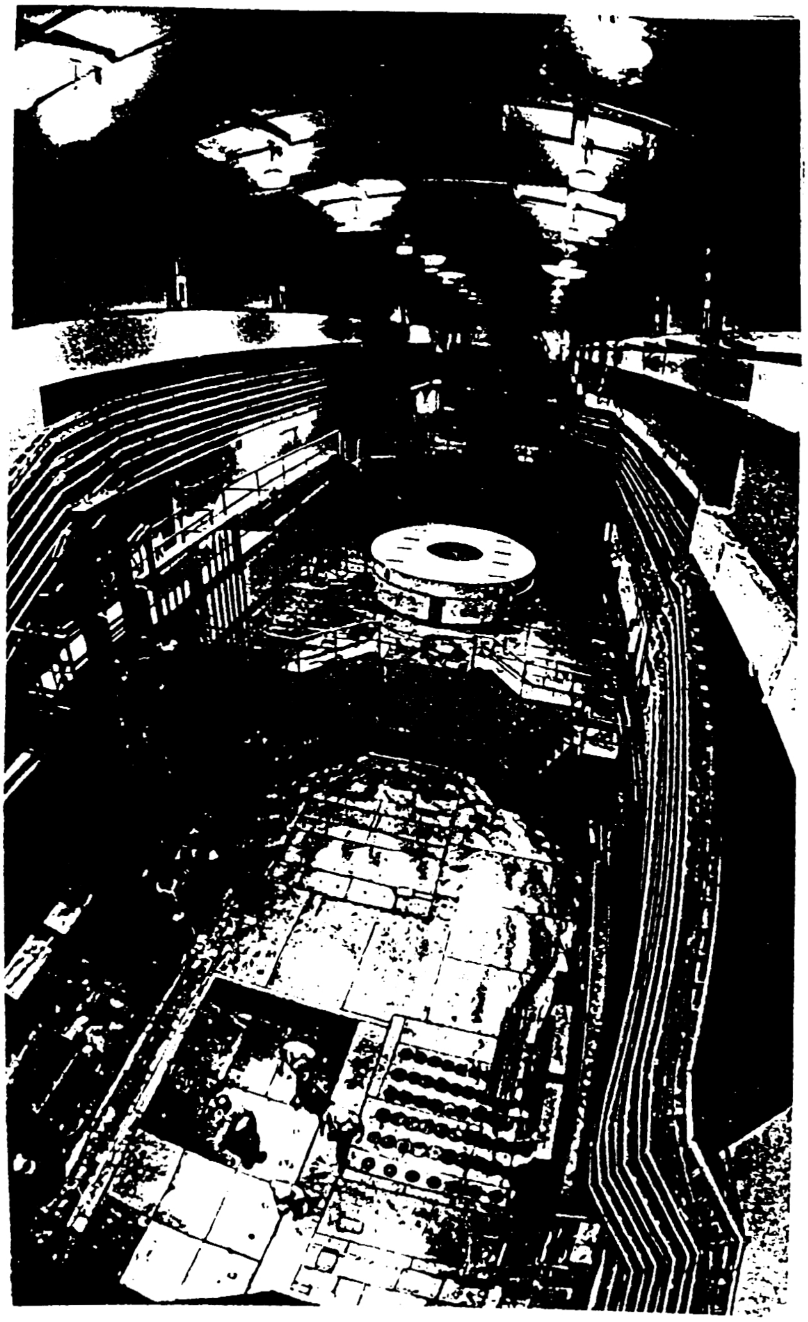

FIG. 2. General appearance of the IBR-2 reactor hall.

It can be seen from these expressions that the width of the neutron pulse determines the resolution in diffraction and inelastic-scattering experiments and that here the basic conditions for the IBR-2 reactor are inferior to those for evaporation sources.

However, the development of the experimental techniques at the IBR-2 shows that the construction of modern facilities makes it possible to obtain a resolution at the level of the best pulsed sources for both elastic and inelastic scattering. This is confirmed by the results of measurements of elastic[16] (Fig. 7) and inelastic[17] (Fig. 8) scattering made on the same samples using IBR-2 and ISIS, which is one of the best evaporation sources (at the Rutherford–Appleton Laboratory, in Great Britain). For small-angle scattering and reflectometry, the width of the neutron pulse is not decisive.

A particularly important development was the construction of the high-resolution Fourier diffractometer,[16] since diffractometry is the most productive direction in which pulse sources are used. At the present time, three such facilities exist in the world: HRPD at ISIS, at HFR, and the above diffractometer at the IBR-2.

The possibilities for performing scattering experiments using IBR-2 are summarized in Table II.

The neutron flux obtained from a reactor depends strongly on the neutron moderator. The moderators used in reactors are usually water, which gives a maximum of the neutron yield with thermal energy. To extend the range of neutron energies and, therefore, the range of effects that can

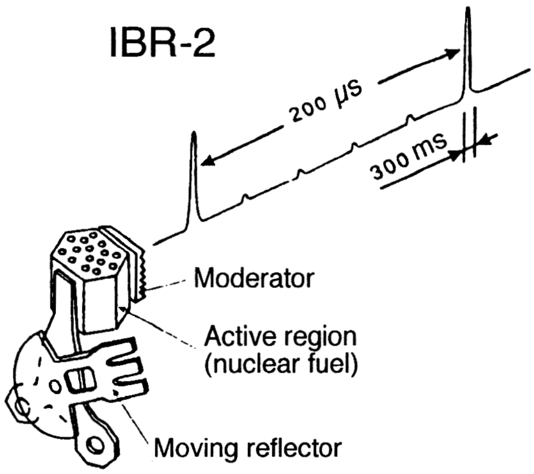

FIG. 3. Basic arrangement of the IBR-2 reactor.

be studied, one uses special devices placed near the reactor core and called cold and hot moderators; these increase the fractions of cold or superthermal neutrons, respectively. Recently, cold moderators have become particularly widespread in connection with the growing interest in long-period structures and slow processes in condensed media.

Tests of a model of a methane cold moderator in the IBR-2 reactor were completed in 1994. The experiments showed that the yield of long-wavelength neutrons can be increased by a factor of more than 10. In view of these results, it is now planned to construct a working moderator with two regimes of operation at 20 K (methane in the solid phase) and at 70 K (methane in the liquid phase). The moderator will be placed in the reactor at the end of 1996.

It should be mentioned that because of the high neutron flux from the IBR-2 there is a relatively large fraction of cold neutrons, and this creates conditions that are better than for other sources for corresponding experiments on diffraction, small-angle scattering, and reflectometry. Of course, the presence of a cold moderator will improve these conditions.

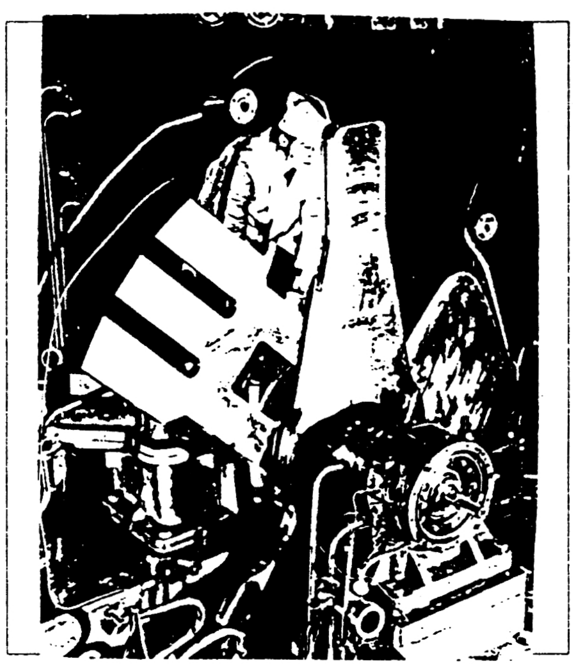

FIG. 4. Moving reflector of the IBR-2 reactor.

The possibilities of periodic pulsed reactors are far from exhausted by the parameters of the IBR-2. The experience gained from the construction and use of such reactors at Dubna shows that such a facility can be designed with parameters better than those of the IBR-2, as regards both the neutron physics and the operation of the reactor.[18] For example, a project that is now ready for implementation is that of a new moving reflector made of a nickel alloy in which the moving parts rotate in opposite directions and which will permit an increase of the flux by a factor of 2 while decreasing the pulse width by a factor 1.5. Work has already begun on a program of modernizing the IBR-2 to be carried out during the period 2002–2004.

Thus, experience gained from operating the IBR-2 shows that the physicists have at their disposal cheap, safe, and effective pulsed neutron sources. As regards the possibilities that it offers, the high-flux IBR-2 is close to evaporation neutron sources and can serve as a good complement to them. Moreover, the experience from operation of the IBR-2 shows that the width of the neutron pulse is not too critical a parameter as regards achieving a high-quality source and that it can certainly be sacrificed in order to achieve a higher flux. A general conclusion is that pulsed neutron sources with large pulse width can be more promising because of their high flux and relative cheapness. Among such sources, we include pulsed sources of the IBR type and evaporation sources based on linear proton accelerators.

BOOSTERS

In the previous section, it was shown that the pulse width of a neutron source, which is an important parameter of it, is not a decisive parameter in the realization of the majority of experiments in the physics of condensed media, provided that the source has a sufficiently high intensity. The situation is different for experiments in nuclear physics, in which neutrons of high energies $E>1$ eV are used and where the "quality" of the source can, admittedly roughly but quite adequately, be characterized by the parameter[9,15]

$$n(E)\sim\Phi(E)/(\Delta t)^{m}, \tag{5}$$

where $n(E)$ is the intensity of the neutron detection for the given uncertainty ΔE in the energy, $\Phi(E)$ is the flux of neutrons in the energy interval ΔE, Δt is the uncertainty in the neutron time of flight, which depends mainly on the duration of the source pulse (after the moderator), and the exponent $m\geqslant 1$ depends on the type of the experiment.

Since for neutrons with $E\geqslant 1$ eV the uncertainty of their migration in the water moderator is $\Delta t = 1.2/\sqrt{E} \leqslant 1\ \mu$s, it can be seen that a neutron source of the IBR type, which gave a duration $\sim$50 μs of the premoderator burst, was not optimal for nuclear physics. Therefore, soon after the IBR reactor was commissioned, it was decided[6] to use the idea of boosters that had been proposed and realized at Harwell (Great Britain) in 1959 (Ref. 19).

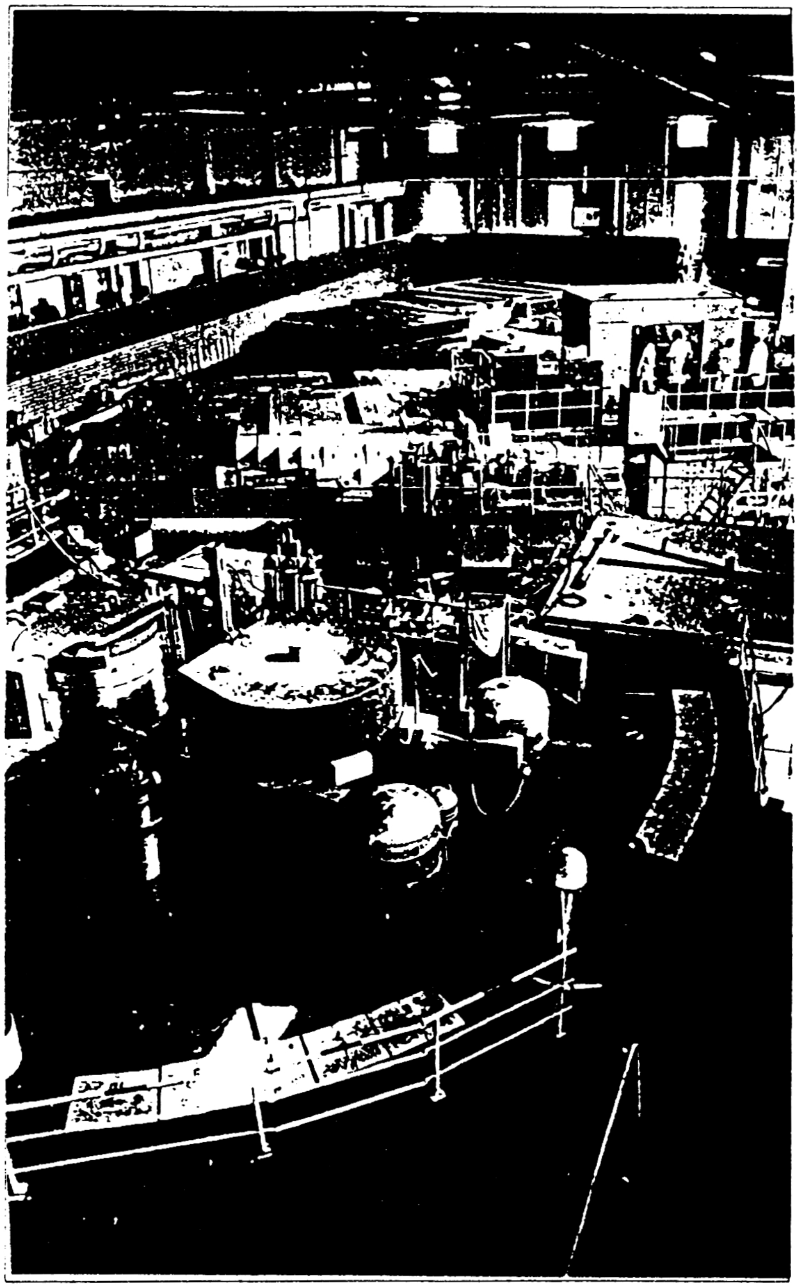

FIG. 5. New moving reflector in the casing of the reactor core.

In 1964, the IBR began to be used as a photonuclear superbooster in a complex with an electron accelerator, in which the reactor played the role of a multiplying target that, in its turn, had modulation of the reactivity. At the end of the sixties and beginning of the seventies, several superbooster projects were published,[20] but, so far as we know, none of them was realized. Up to 1986, the IBR-30 could operate in two regimes—as a periodic pulsed reactor and as a superbooster. In 1986, the reactor regime was terminated. Since the core life will end in 1999, a project for a new neutron source—the resonance neutron source IREN—was proposed.[21] In fact, the proposed range of neutron energies, from $5\cdot 10^{-1}$ to 10^4 eV, has the greatest interest for neutron nuclear physics. With allowance for the general economic situation, the project attempts to optimize the source parameters and minimize the expense of its construction.

The main limiting parameter was the need to retain the existing buildings and beam separation facilities for the physics facilities. Therefore, the arrangement of the facility (Fig. 9) and the neutron beams (Fig. 10) is completely retained. The IREN will be a specialized source for investigations in nuclear physics with resonance neutrons, and therefore the optimum duration of the neutron pulse can be of order 0.5 μs (IBR-30 has 4 μs). To increase the neutron flux, a multiplying target of metallic plutonium is used. The main requirements are on the electron accelerator.

Figure 11 shows the dependence of the yield of photoneutrons on the electron energy per unit power of the accelerator. It can be seen that at an energy of order 100 MeV the curve saturates. It was therefore decided to use an accelerator

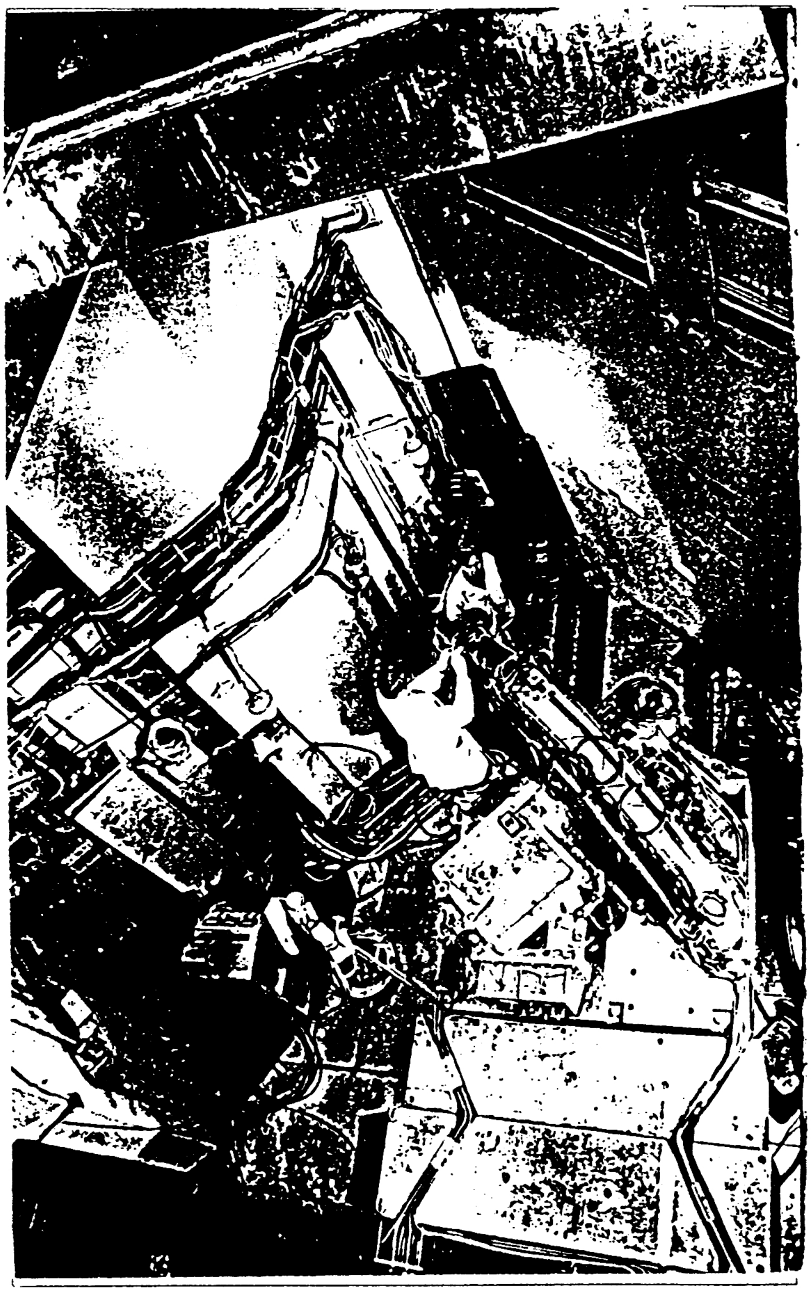

FIG. 6. General appearance of the experimental hall of the IBR-2 reactor.

with energy up to 200 MeV. Such an accelerator was constructed at the Institute of Nuclear Physics of the Siberian Branch of the Russian Academy of Sciences at Novosibirsk.

The IREN parameters, optimized with respect to all conditions, are given in Table III. At the present time, several neutron sources are used for nuclear physics. The most important of them are given in Table IV for comparison with IREN. Besides the source LANSCE at the Los Alamos Meson Factory, the remaining sources are based on linear electron accelerators. Table IV gives the integrated intensities $I_n[n/c]$ and the coefficient C in the expression

$$\Phi(E,L)=\frac{C}{EL^2},$$

which characterizes the flux Φ of neutrons with energy E [eV] at distance L [m] from a source on an area 1 cm^2. We also give the duration of the pulse of fast neutrons (before moderation) and the duration of the pulse of neutrons moderated to 100 eV.

It can be seen from Table IV that as regards its possibilities IREN is inferior to only the source with the highest flux for nuclear physics: LANSCE. However, if it is borne in mind that the cost of IREN is about 3 million US dollars (without the equipment of the buildings), while the annual cost of using the facility will be about 0.5 million US dollars, we can see that IREN will be a very effective source.

It appears that Dubna is the only center in the world in

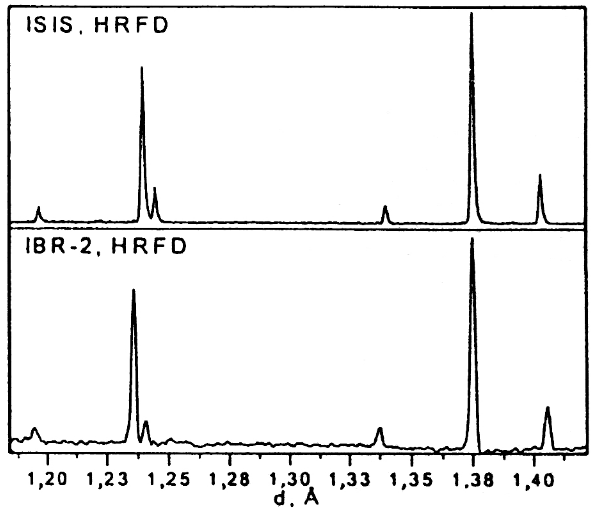

FIG. 7. Part of diffractogram of a standard Al_2O_3 sample measured by means of the diffractometers HRPD at ISIS (at the top) and FDVR at IBR-2 (at the bottom).

which a new booster based on an electron accelerator, indeed any booster, is being constructed. Since boosters raise the neutron yield by a factor 10–100 for practically the same energy expenditure, their use in proton accelerators would naturally be effective. So far as we know, there is only one booster project ready for realization—the neutron-source project at the Moscow Meson Factory at Troitsk.[22] The main reason for this is that boosters belong to the category of nuclear reactors currently actively opposed by the public in many countries. It seems to us that the experience gained at Dubna convincingly demonstrates the efficiency of boosters as cheap and safe neutron sources for physical investigations. There is no doubt that this experience will also be helpful for solving the problems of power generation in the development of electronuclear energy sources.

STATUS AND PROSPECTS FOR THE DEVELOPMENT OF NEUTRON SOURCES WORLDWIDE

The analysis of Ref. 8 shows that the total number of reactors in the world is decreasing and that this tendency will

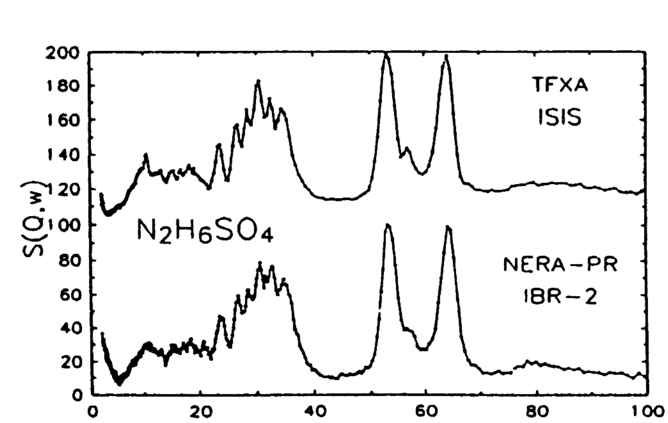

FIG. 8. High-resolution spectra obtained in the case of scattering by hydrazine sulfate, measured using the spectrometers TFXA (ISIS) and NERA-PR (IBR-2).

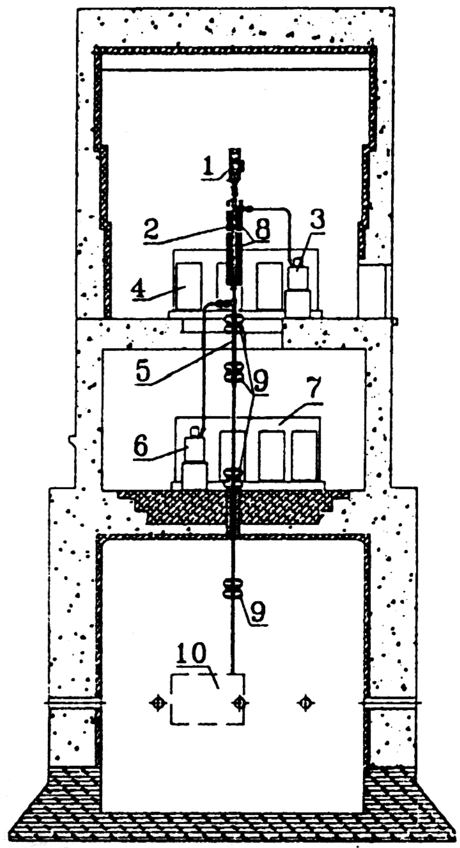

FIG. 9. Arrangement of the IREN facility: 1) Electron source (gun); 2) accelerating sections; 3), 6) SLAC 5045 klystrons; 4), 7) klystron modulators; 5) electroguides (channel for transporting electrons); 8) solenoids of focusing system; 9) quadrupole correcting lenses; 10) multiplying target.

persist in the near future, since the majority of working reactors are already approaching the natural end of their use. It may be expected that among the existing reactors the following will still be operating after 2005: ORPHEE (France), DHRUVA (India), BER-2 (Germany), JRR-3M (Japan), BRR (Hungary), HFR (France), MARIA (Poland), and IBR-2 (Russia). Of these, six are in Europe and two in Asia.

In Europe, the reactor HFR (ILL) was restarted at the beginning of this year after maintenance. It will maintain its leading position as an international center for another 20 years. It is to be expected that next year operation will commence for the constant-flux neutron sources of evaporation time SINQ at PSI (Villigen, Switzerland[23]) and the pulsed source at the linear proton accelerator of the Moscow Meson Factory (Institute of Nuclear Research, Russian Academy of Sciences, Troitsk, Russia). In 1998, the facility IREN at Dubna must begin operation. Improvements of the parameters (raising of the flux and lowering of the pulse width) can be expected from the planned modernization of the reactor IBR-2 during 2002–2004. In the more distant future, one can reckon with the pulsed sources AUSTRON and ESS of evaporation time that are currently being projected.

Realization of the PIK reactor project at Gatchina (Russia) continues.[24] This is a project for a modern third-generation reactor designed for power 100 MW, neutron flux 4×10^{15} neutrons$\cdot$cm$^{-2}\cdot$s^{-1} with two cold and two hot

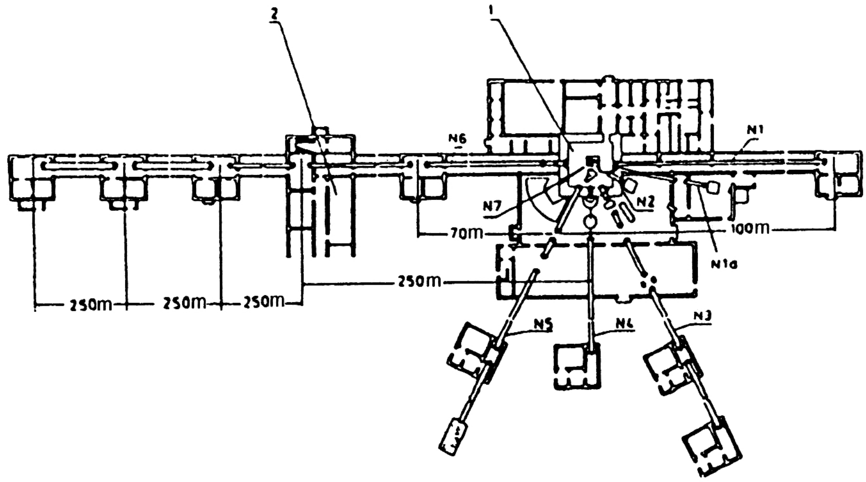

FIG. 10. Arrangement of neutron beams at the IREN facility: 1) Hall of electron beam extraction and target; 2) laboratory frame No. 44; $N1$–$N7$ are the numbers of the neutron channels.

sources, experimental hall (near the reactor) and neutron-guide hall and with total possible number of facilities up to 50. So far, about 80% of all the work has been done, this taking into account the new safety requirements introduced in Russia after 1986. The PIK reactor could play the role of a European neutron center, considering its convenient situation (40 km from St. Petersburg on the side of the international airport) and the existence of the highly qualified and very experienced personnel at the St. Petersburg Institute of Nuclear Physics of the Russian Academy of Sciences.

With regard to reactors of intermediate power, one can expect further development of the international collaboration at the reactors mentioned above with the aim of improving their infrastructure and making more efficient use of them.

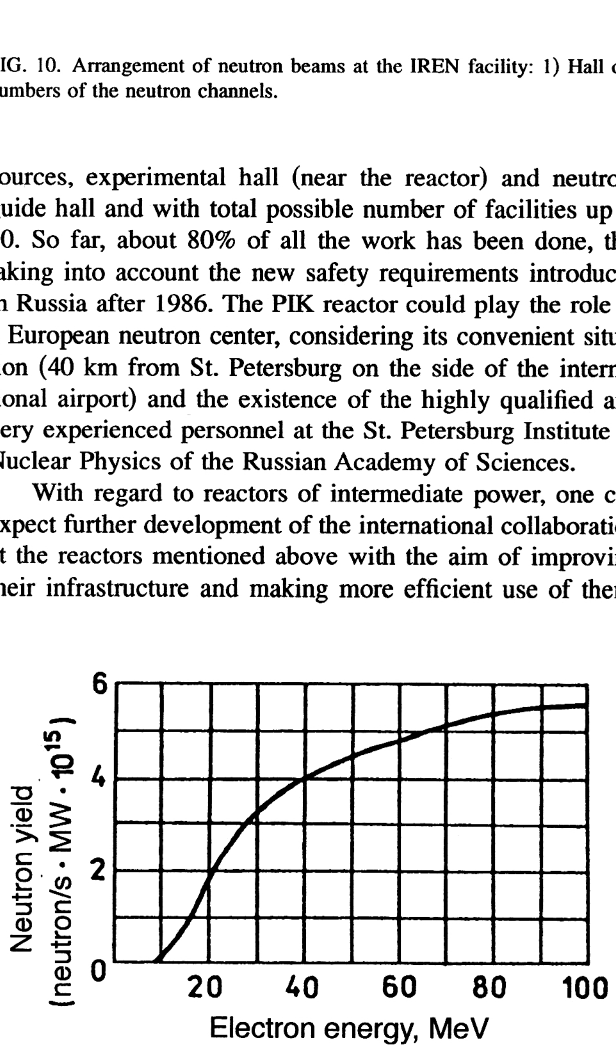

FIG. 11. Dependence of photoneutron yield on the electron energy per power unit.

TABLE III. Basic parameters of IREN.

Accelerator		Multiplying target	
Electron energy, MeV	200	Multiplication	30
Pulsed current, A	1.5	Pulse width, μs	0.4
Pulse width, μs	0.25	Mean neutron intensity, s^{-1}	$1.5 \cdot 10^{15}$
Repetition frequency, Hz	150	Volume of core, dm^3	2.5
Mean power, kW	12		

Among the new projects, a very attractive one is that of building a 20-MW reactor at Garching (Munich, Germany); this project takes into account experience gained from the reactor ORPHEE. It is possible that a decision to build it will be taken this year.

In the United States, there are several proposals to build a reactor of the type of HFR at ILL and a pulsed source of evaporation type of power 1 and 5 MW. Although all these proposals are in the evaluation stage, it is clear that in the United States new projects for neutron sources must begin to be realized in the coming years, since the existing reactors were commissioned in the middle of the sixties. After the stopping at the beginning of this year of the project of the superreactor ANS at Oak Ridge, the next reactor can be expected to be a proton accelerator, probably a linear one without storage.

In Canada, the dominant concept is that of using international megafacilities together with one or two domestic reactors of intermediate class. Two projects are being considered: modernization of the MNR reactor with increase of the power to 12 MW (the cost will be between 70 and 120 million US dollars), and replacement of the NRU reactor at Chalk River by a new 20-MW reactor costing 150–200 million US dollars.

In Asia, neutron studies in the coming years will be

TABLE IV. Parameters of the most intense pulsed neutron sources for nuclear physics.

Source	$\langle I_n \rangle \times 10^{-15}$	$C \times 10^{-7}$	τ, μs	Δt (100 eV), μs
FAKEL (RNTs KI, Russia)	0.03	0.1	0.05	0.2
ORELA (ORNL, USA)	0.13	1.5	0.03	0.18
LUÉ-40/IBR-30 (Dubna)	0.5	2.7	4.00	4.1
LANSCE (LANL, USA)	10	40	0.150	0.3
IREN (Dubna, project)	1.0	5	0.4	0.43

TABLE V.

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largely concentrated at the reactors JRR-3M (Tokaimuri, Japan) and DHRUVA (Bombay, India). As regards new projects, sources based on accelerators have so far been discussed in Japan.

In Australia, there are plans to reconstruct the existing reactor and build a new source.

In Egypt, work has begun on the construction of a new 22-MW research reactor at the Atomic Energy Organization in Cairo.

Thus, best prepared for the transition to the next stage in the development (after 2000) of neutron reactor sources is Europe, where in the seventies and eighties there was a significant development in both reactor technology and experimental methods. However, here too great efforts will be needed to maintain progress. This is due not only to technical and financial difficulties. A great problem is the fear, which has grown greatly in recent years, of nuclear disasters and the risk of proliferation of nuclear weapons. A serious role may be played by the restriction introduced in the United States on enrichment of ^{235}U to 20%. Since the United States is one of the main suppliers of nuclear fuel, this restriction will automatically lead to a lowering of the power and, therefore, the neutron flux density in both existing and future reactors.

CONCLUSIONS

The use of neutrons for physics research has such a great value that, despite all the difficulties—increasing cost of running the existing reactors and designing and constructing new reactors, restrictions on the fuel, and resistance of the "green movement"—it is continually winning new adherents. The number of users of neutron beams, including reactor beams, is increasing. According to data presented at the Megascience Forum Experts' Meeting on Synchrotron Radiation Sources and Neutron Beams (November 29–December 1, 1993, Riso, Denmark) organized by the OECD,[25] the total number of users in just the countries of the OECD was estimated at ~4000 in 1993 and is expected to be ~7000 in the year 2000. Thus, the need for neutrons for science dictates a need to have an appropriate number of neutron sources.

At the present time, nuclear reactors are the most common sources of neutrons for physical investigations, and the need for them will remain for a long time. The desire to avoid possible nuclear disasters is the reason for the general tendency to develop evaporation sources based on proton accelerators. From this point of view, the optimum route is evidently the construction of the cheaper, given the existence of one or two large storage facilities of ESS type, proton boosters, i.e., powerful linear proton accelerators with a multiplying target. In this sense, the experience gained from using periodic pulsed reactors of the IBR type is very important, both from the point of view of operating with boosters and from the point of view of the development of experimental methods with a pulsed source and large width of the neutron pulse.

Thus, it can be asserted with confidence that the periodic pulsed neutron sources at Dubna developed with the active participation of F. L. Shapiro are effective, economic, and cheap devices that give good possibilities for physical studies using neutrons. They play an important role in the formation of ideas and technical solutions in the construction of new neutron sources throughout the world. All this amounts to an objective justification for further development of the periodic pulsed reactor IBR-2 and the electron booster as original modern neutron sources.

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