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REACTOR NEUTRON SOURCES

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1. Introduction

Nuclear research reactors as neutron sources have become world-wide in their distribution since the late '50's. This, to a large extent, was mediated by the activities of the International Atomic Energy Agency (IAEA) established by the Organization of United Nations in 1957. The IAEA has accomplished much in promoting the use of natural uranium for nuclear fuel production, the creation of nuclear reactors, organization of their safe operation, and their use in isotope production for medicine, agriculture, etc. The result was that in the '60's every industrially developed country had or was making efforts to have nuclear reactors.

From the very beginning, in addition to radiation research and isotope production, nuclear reactors were used for physical research in neutron beams. These investigations appeared to be so informative and important for the solution of the problems of nuclear physics and condensed matter physics that in the mid-'60's, the construction of neutron sources optimized for beam research began. The most wide-spread has become the neutron-aided investigations in condensed matter physics. At present the region of accessible transmitted energies is from 100 neV to several ten eV, and of momentum transfers from 10^{-4} $Å^{-1}$ to 10^{2} $Å^{-1}$ The possibility of varying these parameters over the interval of six orders of magnitude permits one to investigate fundamental interactions, the properties of solids, liquids, biological objects, and chemical reactions. During the last two decades a diversity of new scientific results were obtained which were beyond the reach of other experimental methods.

At the same time, in the early '90's, the number of neutron sources in the world started to decrease steadily and it may probably go down to the level of the '60's by the beginning of the next century. This decrease is due to several reasons. First, the reactors built in the late '50's to early '60's are being shut down, and the public opinion of many countries is strongly against the construction of new ones. Second, the spallation neutron sources, on the basis of proton accelerators, have been created. These sources are fairly effective, although their construction requires large time and money investments. Third, investigations at synchrotron radiation sources have become wide-spread, nowadays. These investigations nicely complement the neutron-aided investigations and reduce the demand for the latter.

Hence, the current situation in neutron sources in general, and of reactor neutron sources in particular, demands discussion and a coordination of efforts on the international level, because the above reasons for the decrease in the number of neutron sources are closely connected with general scientific and social processes.

In this paper an attempt to analyze the situation of reactor neutron sources in the world is made. The paper does not contain detailed information about the reactors, because in my opinion, during the time allocated for the report it is more important to discuss general issues. The present state of and the prospects for the development of neutron sources were given detailed consideration at the OECD Megascience Forum Experts Meeting on Synchrotron Radiation Sources and Neutron Beams held November 29 - December 1, 1993 in Risø, Denmark. In preparing this report I orientated myself to the sources used mainly for pure physical research, and this has inevitably brought a certain degree of subjectivism. Therefore, I wish to apologize in advance for the possible inacuracies and will be grateful for any corrections.

2. Use of Neutrons

In modern physics neutrons are used to investigate the fundamental interactions, including the neutron life-time, parity and time reversal symmetry violation effects, and the structure of the nucleus, but most intensively for investigations in the fields of condensed matter physics, biology, chemistry, and nondestructive testing of materials and industrial products.

In these fields the following large research areas can be separated out: crystallography, magnetism, liquids, including superfluid and amorphous bodies, surfaces and layered systems, biological membranes, proteins, chemical reactions, polymers, material aging, element analysis, internal stresses, and texture. It is necessary to emphasize that the majority of the above investigations are not only directed to the study of the properties of new materials, although it is important too, but also to the new phenomena which condensed matter physics unceasingly supplies the natural sciences with. One of the latest examples of the decisive role of neutrons in the study of new physical phenomena is decoding the structure of high temperature superconductors.

In the research fields alluded to above, the synchrotron radiation sources are beginning to be more and more widely used. The main advantage of these sources is their high luminosity and the possibility of switching to different energy regions. This does not mean, however, that synchrotron radiation sources exclude neutron sources. On the contrary, these two methods are complementary. Neutrons have properties which clearly set them off from the other particles, including photons, electrons, muons, and protons used for investigations in condensed matter.

Neutrons interact in matter with both the nuclei and the electron spins of atoms. The most important feature of these interactions is that they are the weak interactions: the neutrons do not violate the structure or chemical properties of the matter as the interactions taking place, as in photoemission. Therefore, to calculate the scattering cross section one may limit oneself to the first approximation of the perturbation theory. Weak interaction favors the large penetration depth of neutrons in a sample, as different from photons, which permits investigation of volume structures and dynamical properties in elastic and inelastic neutron scattering experiments. At the same time neutrons also permit the investigation of surfaces which is a nice complement to X-ray investigations, specifically in the study of magnetic systems. The nuclear scattering amplitude is determined by the properties of nuclear forces and has an isotopic dependence. The isotopes of one element may have amplitudes of different signs which provide the unique possibility of isotopic contrast in the investigated sample. Besides, the scattering amplitude does not depend on atomic number in a regular manner as in the case of photons. Light elements, like hydrogen, have an essentially larger amplitude, and this allows the neutron to effectively "highlight" these elements in the investigated structure.

The above properties are complemented by the remarkable fact of the exact correspondence of the wave length of thermal neutrons, $\lambda \sim 1 - 10$ Å and their energy, $E_n = 1 - 100$ meV, with the typical interatomic distances in solids and liquids as well as with the characteristic excitation energies. Hence, a thermal neutron source permits investigation of both the structure and the dynamics of matter.

With more intense neutron sources the possibilities for neutron research broaden. This is not only due to the reduction of the time of experiments, but also because of the opened possibilities, among which are the possibility of an increase in the precision of measurements, the study of smaller samples, the study of complex objects and objects with small scattering cross sections, and the performance of experiments with an analysis of the neutron polarization before and after scattering.

Table 1 illustrates the most widely used methods for neutron production. Historically, the first intense sources of neutrons were nuclear reactors, where a continuous flux of neutrons was generated in the process of the spontaneous fission of uranium. In nuclear reactors with a continuous neutron flux there are limitations on the allowed neutron flux. These are due to technological reasons connected mainly with heat removal problems. In this sense the pulsed reactors where the modulation of reactivity increases the yield of neutrons useful for beam research by a factor of 100-200, open certain prospects.

Table 1 The most widely used methods for producing neutrons for physical investigations.

Reaction	Number of neutrons	Examples	Target power, MW	Neutron flux, n cm^{-2} s^{-1}
Fission	2 fission	HFR, Grenoble	57	$2\;10^{15}$
Modulation of reactivity, reflector	x 100-200	IBR-2, Dubna (pulsed)	2	10^{16}
(e,γ), (γ,n) in a heavy metal target	$5\;10^{-2}$ 100 MeV	ORELA, Oak Ridge	0.05	$1.3\;10^{14}$
Multiplicating target, Pu	x 20	IBR-30, Dubna	0.01	$5\;10^{14}$
		IREN, Dubna (project)	0.01	10^{15}
Proton spallation	30 800 MeV	ISIS, London	0.2	$1.3\;10^{15}$
Multiplicating target ^{233}U	x 20	IN-0.6, Moscow (project)	2	$2\;10^{16}$

Another type of source uses the photonuclear reaction and linear electron accelerators for neutron production. Because the output of neutrons from the photonuclear reaction is small: 1 neutron per 20 electrons with an energy of 100 MeV, the use of a multiplying target (booster) and a multiplying target with reactivity modulation (superbooster), to increase the neutron yield using the operational experience of the pulsed reactors, appeared effective.

With respect to neutron production the most effective is the spallation reaction triggered by a proton synchrotron: ~ 30 neutrons per 1 proton with the energy of ~ 800 MeV. The use of a multiplying target might increase the neutron output by about another 20 times.

In the creation of high flux neutron sources the modern trend is towards the spallation sources. At the same time the development of reactor sources still remains viable because of a number of reasons. First, the proton synchrotrons with the necessary parameters are fairly complicated and expensive machines. Second, the realization of powerful target facilities meets the typical reactor problems, such as heat removal and the radiation resistivity of construction materials, which is determined by the density of the fast neutron flux in the centre of the core or target. And finally, nowadays, there is still a sufficiently large number of working reactors in the world which have good prospects for development. In what follows we shall consider the present status of reactor neutron sources for physical research.

3. Steady State Reactors

There are numerous reviews on steady state reactors. Beginning from 1990 "Neutron News"[1] regularly publishes detailed reports on neutron sources. Detailed reviews on the reactors of Asia[2] and Europe[3], as well as the reactors of Japan[4], Russia[5,6] and the USA[7,8] were submitted to the International Conference on Neutron Scattering in Bombay in 1991. Referring the reader to the above publications for details, I shall concentrate on the qualitative picture and present tendencies.

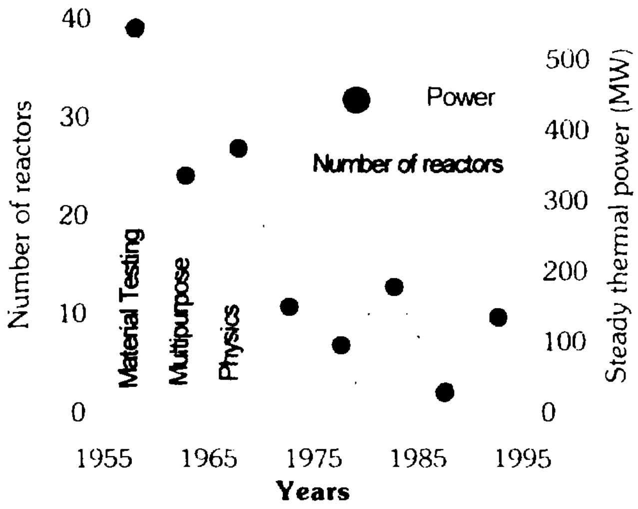

Fig. 1 The number of reactors started and their generated power versus corresponding periods of time (in the world).

Figure 1 shows the number (and thermal power) of reactors started, for five-year periods, from 1955 to 1994. As is seen the largest number of reactors were put in operation in the 1955-1960 period. These were the first generation reactors dedicated to irradiation and radiation research. After 1960 the second generation reactors dedicated to both radiation research and investigations in neutron beams began to be built. The first reactor of the third generation, i.e., the reactor optimized for beam research, was built at Brookhaven in 1965. It was the 60 MW HFBR reactor.

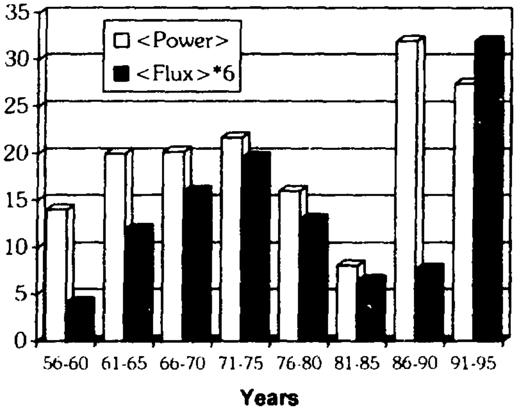

Fig. 2. The dynamics of the thermal power and neutron flux density of reactors related to the year of their startup (in the world)

The evolution of research reactors can be followed in Fig.2. Till about 1960 neutron flux increased at the same rate as the increase in reactor power. After 1960, the further increase in neutron flux began taking the lead over the increase in reactor power. This lead became most noticeable beginning from the early '70's when the intense use of third generation reactors, such as HFR at ILL (Grenoble, France), ORPHEE at LLB (Saclay, France), IR-8 at Kurchatov Institute (Moscow, Russia), IBR-2 at FLNP JINR (Dubna, Russia), etc., began.

Currently in the world there are about fifty research reactors where investigations in neutron beams are conducted. The main part of them is listed in Table 2. As is seen from Fig.3 the majority of these reactors are reactors which have worked for over 30 years and this period is very close to the service life of a reactor. Therefore, the greatest part of them needs modernization or replacement.

Table 2. Reactors for neutron scattering measurements

Country	Reactor	Location	Criticality (year)	Power (MW)	Thermal Flux (10^{14} n/cm^2/s)	Cold source	Instru -ment
Australia	HIFAR	Lucas Heights	1958	10	1		8
Austria	ASTRA	Vienna	1960	10	1.4		5
Banghadesh	TRIGA-II	Dhaka	1986	3	0.5		1
Belgium	BR2	Mol	1962/63	85	12		4
Canada	NRU	Chalk River	1957	125	3		6
	MNR	McMaster	1959	1	0.2		7
Czech Rep.	WWR	Rez	1974	10	1		4
China	HWRR	Beijing	1958/80	15	2.8	1	5
Denmark	DR-3	Risø	1960	10	1.5	1	7
Egypt	WWR	Cairo	1961	2	0.1		3
Finland	FIR-3	Espoo	1962	0.25	0.1	1	3

- continued

Table 2. Reactors for neutron scattering measurements (continued)

France	SILOE	Grenoble	1962/87	35	4		6
	HFR-ILL	Grenoble	1971/94	58	15	2	32
	ORPHEE	Saclay	1980	14	2.5	3	22
Germany	FRM	Garching	1957	4	0.2	1	10
	FRJ-2	Jülich	1962/72	23	2	1	18
	FRG	Geesthacht	1963	5	0.5	1	7
	FRMB	Braunschweig	1967	1	0.14		5
	BER-II	Berlin	1973/91	10	1	1	14
Greece	GRR-1	Athens	1959	5	0.5		1
Hungary	WWR	Budapest	1992	10	1		10
India	CIRUS	Bombey	1960	40	0.6		4
	DHRUVA	Bombey	1985	100	2	1	13
Italy	TRIGA RC-1	Rome	1967	1	0.3		3
Japan	JRR-3M	Ibaraki	1990	20	2	1	20
Korea	KMRR	Seoul	1992	30	5		
Netherlands	HFR	Petten	1961/70	45	1		7
	HOR	Delft	1963/68	2	0.2		8
Norway	JEEP2	Kjeller	1966	2	0.25	1	7
Poland	MARIA	Swierk	1974/94	30	3.3		
Portugal	RP-1	LNETI	1961	1	0.12		2
Roumania	WWR	Bucharest	1958	8	0.8		3
Russia	WWR-M	Gatchina	1959	16	1		12
	WWR-C	Obninsk	1964	13	1		4
	IWW-2M	Ekaterinburg	1966/83	15	2		6
	IRT	Moscow	1967/75	2.5	0.3		4
	IR-8	Moscow	1981	8	1		10
	IBR-2 (pulsed)	Dubna	1984	2/1500	0.1/100	1	14
Sweden	R-2	Studsvik	1960	50	4		8
Switzerland	SAPHIR	Villigen	1957/84	10	1		4
US	MITR-II	Cambridge	1958	5	1		6
	RINSC	R.Island	1964	2	0.14		2
	HFBR	Brookhaven	1965	60	9	1	15
	HFIR	Oak Ridge	1966	100	30		10
	MURR	Missouri	1966	10	1.2		14
	NBSR	Gaithersburg	1969	20	4	1	9

The neutron flux generated by a reactor essentially depends on the neutron moderator. Usually in reactors, water is used as a moderator which provides maximum neutron yield at thermal energies (see Fig.4). To extend the neutron energy range and, consequently, the range of the investigated phenomena, special devices are used which are positioned near the core of the reactor and are called cold or hot moderators, because these moderators, help increase the portion of cold or epithermal neutrons, respectively. Recently, cold moderators have become the most wide-spread because of the growing interest in long-period structures and slow processes in condensed matter. Today, practically all leading neutron centers have cold moderators, which are mainly liquid hydrogen moderators, at their reactors. In Japan (Tsukuba) and Russia (Dubna) scientists also have the experience of working with solid methane moderators.

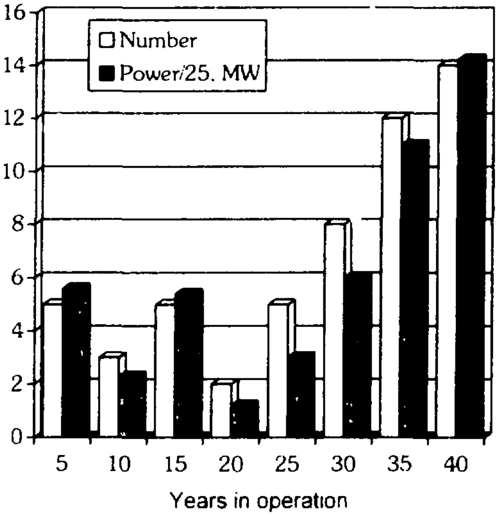

Fig. 3. The age of the existing reactors in the world (according to Table 2)

At several reactors for fundamental research mainly the ultracold neutrons first observed experimentally in Dubna in 1968 are used. Later, investigations of the methods of ultracold neutron production and performing experiments with them were successfully continued at PINP (Gatchina), at ILL (Grenoble) and Kurchatov Institute (Moscow).

In the long run the efficiency of a reactor's work is defined by the efficiency of its experimental instruments. Table 3 exemplifies the reactors of the third generation, and partly of the second generation, which are mainly orientated to beam research (with consideration for the provisos made in the Introduction). According to the generally accepted classification the measuring instruments can be divided into five types: diffractometers for elastic and diffuse elastic scattering, small angle scattering setups, reflectometers, spectrometers for inelastic and back scattering, and some specific devices. The latter category includes all instruments that fall outside the first four groups. Instruments for irradiation and activation analysis are not considered here. As is seen from this Table, the HFR of the high power reactors and the ORPHEE of the medium power reactors are the most effective reactors in all parameters. The HFR reactor has the largest absolute and specific (power reduced) neutron fluxes, and the most developed infrastructure for conducting experiments. The organization of work at ILL is a good example of international cooperation. By the way, one of the main reasons of ILL's success is that the institute renews its instruments every 10-12 years, which, though expensive, ensures the high level of research. The ORPHEE reactor as well as the IR-8 reactor seem to be optimal as medium power reactors, and the organization of work on them is a good example of how it should be done at a national centre.

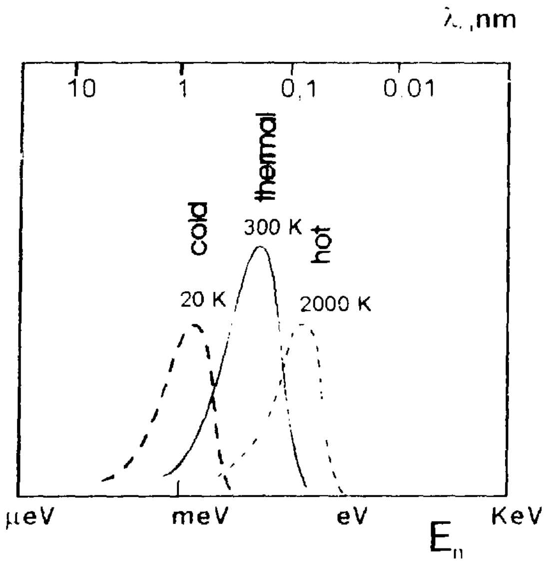

Fig. 4. Spectral distribution of the neutron flux from steady-state reactors

Besides technical characteristics, the most important parameter is the cost of a facility. The cost of a reactor is to a great extent determined by its mean power. Therefore, the conditional characteristic determining the cost of neutron production can be considered the ratio of flux density to mean reactor power. Then, the conditional characteristic of reactor use efficiency is the above ratio multiplied by the number of experimental instruments. Fig.5 illustrates these characteristics of an "average reactor" for different periods of time, and shows the same characteristics for the HFR, ORPHEE and IBR-2 pulsed reactors for comparison Fig.5 summarizes pictorially the advantages of the HFR and ORPHEE reactors over the other steady state reactors. The IBR-2 pulsed reactor is very distinguishable with respect to the above discussed parameters and, therefore, it will be discussed separately in the next section.

So, looking at Table 2, one may think that the number of reactors in the world is sufficiently large. Not all of them, however, completely satisfy the requirements for facilities for physical research. Since the first specialized reactor of the third generation, the HFBR reactor, was commissioned at BNL in 1965, only about ten updated reactors of the same type have been put in operation. By and large, in spite of the fact that the ways for increasing the usage efficiency of reactors were fairly well developed in recent years, e.g., moderators, neutron guide systems, and updated spectrometers, the number of reactors updated for physical research is clearly insufficient to meet the increasing demand from scientists engaged in physics, biology, chemistry and materials science.

Table 3. High flux research reactors and their instrumentation suites

Country	Reactor	Location	Year	P (MW)	Flux 10^{14}* n/cm^2/sec	Beam ports include guides	Special moderator	Instruments for Neutron Scattering					
								Diffr.	SANS	Reflect.	Spectr.	Special Instr.	Total Instr.
Canada	NRU	Chalk River	1957	125	3	6	C	3	1	0	2	0	6
Denmark	DR-3	Risø	1960	10	1.5	4	C	1	1	0	5	0	7
France	SILOE	Grenoble	1962/87	35	4	3	-	4	0	0	2	0	6
France	HFR-ILL	Grenoble	1971/94	58	15	26	2C,1H	13	2	0	12	5	32
France	ORPHEE	Saclay	1980	14	2.5	20	2C,1H	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	Bombey	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
Netherlands	HFR	Petten	1961/70	45	1	12	-	3	1	0	2	1	7
Russia	WWR-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	IWW-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
Switzerland	SAPHIR	**Villigen**	1957/84	10	1	4	-	2	0	0	2	0	4
US	HFBR	Brookhaven	1965	60	9	9	C	3	3	1	6	2	15
US	HFIR	Oak Ridge	1966	100	30	4	-	4	1	0	5	0	10
US	MURR	Missouri	1966	10	1.2	6	-	3	2	1	2	6	14
US	NBSR	Gaithersburg	1969	20	4	5	C	2	0	0	6	1	9

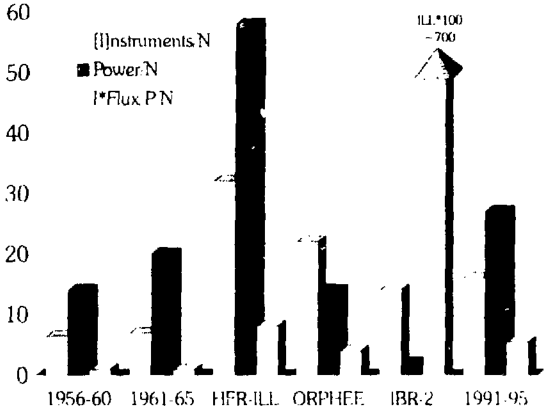

Fig. 5. The number of instruments (I), thermal power (P), and the parameter I multiplied by flux density divided by P, for the average reactor for different periods of time in comparison with the same characteristics for the HFR, ORPHEE and IBR-2 reactors

4. Pulsed Reactors

The history of pulsed reactors began as early as 1945 with the Manhattan Project. These reactors are classified by three types:[9] fast burst reactors, fast pulsed reactors (pulsing), and boosters. Reactors of the first type are the most widely used, and mainly for radiation research, because of the possibility of having a huge peak flux. Systematical beam research is rarely performed with these reactors because of their pulse aperiodicity and the consequently low average flux. An example of the use of a superhigh power reactor is the experiment on the measurement of neutron life time with an instrument producing ultracold neutrons with a record density of 10^5 n/cm^3 (for comparison, this density is 10^2 n/cm^3 from the ILL source). This experiment is now under preparation by the FLNP group at the BIGR reactor in Arzamas-16, Russia. The exception is the TRIGA type reactor whose virtually immediate negative temperature coefficient ensures the highest safety. Therefore, these reactors are wide-spread, now. The first TRIGA 1 reactor started operation in the USA in 1958. At present there are 65 such reactors in the world, which are mainly used for educational purposes and in the continuous operation mode.

The idea of the fast pulsed reactor was first advanced in 1955 in Obninsk (Russia)[10]. Construction of the reactor under the supervision of D.I.Blokhintsev began in Dubna in 1957. The reactor's start at a mean power of 1 kW and a pulse frequency from 5 to 50 Hz took place on June 23, 1960. Since 1964 the IBR reactor has been used as a photonuclear superbooster, i.e., the reactor in combination with an electron accelerator played the role of a multiplying target with reactivity modulation. In 1969 the reactor power was increased to 25 kW and the electron accelerator was replaced by a 40 MeV linear electron accelerator. The new facility was given the name IBR-30. Since 1986 the IBR-30 has been working without reactivity modulation, i.e., as a photonuclear source with a multiplying target (booster) at the mean power of 10 kW, with a thermal neutron density in the pulse of 5×10^{14} n/cm^2/sec, and a pulse width of 3-4 μsec.

In 1984 the new IBR-2 pulsed reactor, whose design is different from the first IBR's, was commissioned in Dubna. This reactor generates a record thermal neutron flux in a pulse of 10^{16} n/cm^2/sec from the surface of the moderator at a mean power of 2 MW. The principal scheme of this reactor is shown in Fig.6. The core of the reactor has a 22 *l* volume and contains 82 *kg* of plutonium dioxide. The reactivity modulation is accomplished by a steel movable reflector which consists of two parts rotating at different speeds. As these two parts simultaneously pass by the core a power pulse develops (1500 MW). For the regular operation of the reactor of 2500 hours a year for physical experiments the service period of the core without fuel renewal is not less than 15 years, and the service life of the movable reflector is 5-7 years. Thus, the IBR-2 is a relatively inexpensive machine, determined by its mean power, and as the ten-year experience of its work has shown, it is easy and safe to operate.

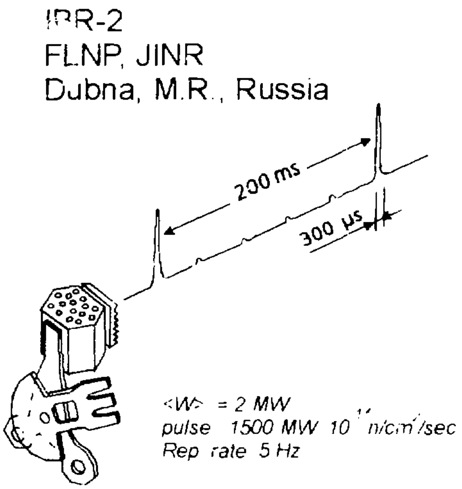

Fig. 6. The principal scheme of the IBR-2 pulsing reactor

The thermophysical characteristics and kinetics of the IBR-type reactors are very close to those of steady-state reactors. Therefore, fast pulsed reactors are closer to the latter than fast burst reactors, and it would be more correct to call them pulsing reactors.

Having the world's highest peak thermal neutron flux, the IBR-2 pulsing reactor is still inferior to spallation neutron sources with respect to pulse width (~ 300 μsec). This fact is frequently noted as a disadvantage of the pulsed reactor, because this characteristic of the source greatly influences the resolving power of the measuring instruments. However, the development of experimental techniques for the IBR-2 shows that the creation of updated instruments permits achieving a resolution on the level of the best pulsed sources both for elastic and inelastic scattering. To support the above statement one may present the results of the measurements for elastic[11] (Fig.7) and inelastic[12] (Fig.8) scattering which were carried out with the same samples at the IBR-2 reactor (JINR, Russia) and the ISIS facility (RAL, UK), one of the best neutron sources in the spallation class. For small-angle and reflectometry measurements the width of the neutron pulse is not the decisive parameter.

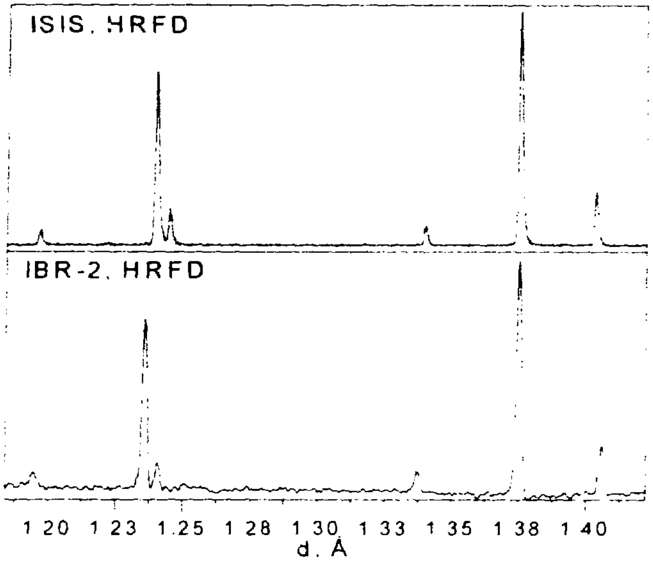

Fig 7 Section of the diffractogram of the Al_2O_3 standard sample as measured with the HRPD diffractometer at ISIS (above) and the HRFD diffractometer at IBR-2 (bottom)

Of special importance was the creation of the high resolution Fourier diffractometer (HRFD)[11], because diffractometry is the most productive direction for the use of pulsed sources. Currently in the world there are three instruments in this class. They are the HRPD at ISIS, DN-2 at HFR, and the HRFD at IBR-2.

The potential of the pulsing reactors is not exhausted on reaching the parameters of the IBR-2 reactor. The experience of the construction and operation of such reactors in Dubna shows that the facility might be designed with parameters better than the IBR's neutron-physical and operational characteristics.[13] For example, the project for the new movable reflector of nickel alloy with the moving parts rotating in opposite directions is ready for realization. This movable reflector would give a two-fold increase in neutron flux at a decrease in pulse width by 1.5 times.

Hence, the working experience of the TRIGA and the IBR-2 reactors shows that physicists have relatively inexpensive, safe and effective neutron sources at their disposal. This is especially true about the IBR-2 pulsing, high flux reactor whose possibilities are very close to those provided by spallation sources and can be a good complement to the latter. Moreover, the operational experience of IBR-2 shows that the width of the neutron flux is not crucial in achieving a good quality source and to have a higher flux is more important. Our experience has shown that for pulsed machines the assumption[14] is true that for the ideally designed instruments requiring neutron monochromatization, the time averaged neutron flux is equal to the peak flux. The general conclusion is that the pulsed neutron sources with a large pulse width might be the most prospective neutron sources because of the high neutron flux and the relatively low cost. Among these sources are the linear proton booster (the spallation multiplying target with the linear proton accelerator) and the pulsing reactors of the IBR-type.

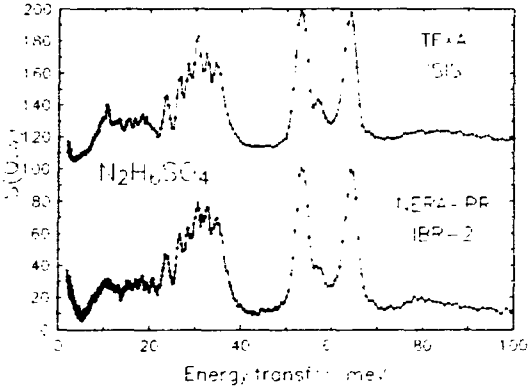

Fig. 8. The high resolution spectra of neutron scattering on hydrazine sulfate measured with the TFXA (ISIS) and the NERA-PR (IBR-2) spectrometers

5. Foreseeable Prospects

As is seen from the data illustrated in Fig.3 the total number of reactors in the world is decreasing and this tendency will continue, because the majority of the working reactors are approaching their service life expiration dates. It might be expected that of the existing reactors only the high flux reactors: ORPHEE (France), DHRUVA (India), BER-2 (Germany), JRR-3M (Japan), BRR (Hungary),HFR (France), MARIA (Poland), and IBR-2 (Russia) will remain in service after 2005. Six of these reactors are in Europe and two are in Asia.

In EUROPE, after its shutdown for repair, the HFR reactor of ILL will resume operation at the end of this year, and ILL will be able to retain its leading position as an international centre for another 10-20 years. Next year the spallation neutron source with a continuous flux, SINQ in PSI (Villigen, Switzerland[3]) and the pulsed source with a linear proton accelerator of the Moscow Meson Factory at the Institute for Nuclear Research of the Russian Academy of Sciences (Troitsk, Russia[15]) will most probably be started. The improvement of parameters (an increase in flux at a reduced pulse width) might be expected as the result of the projected modernization of the IBR-2 in 1997-1998. Further in the future, after 2010, one might count on the European projects currently under development: the powerful neutron source of the spallation type AUSTRON and ESS (see the report of H.Lengeler to this Conference).

Unfortunately, the PIK reactor project remains unrealized in Gatchina (Russia)[5]. This is the project of a third generation reactor with a rated power of 100 MW, neutron flux of 4.5×10^{15} n/cm²/sec, two cold and two hot sources, and the experimental hall near the reactor and the neutron guide hall capable of housing a total of up to 50 experimental setups. About 80% of the work with consideration for the new nuclear safety regulations adopted in Russia after 1986 has been done at present. If the project were realized (for that the sum of about 30 mln US$ is needed), the PIK reactor could play the role of a European neutron center because it has a very convenient location (40 km from St.Petersburg's international airport) and the highly qualified and experienced staff of PINP RAS.

As for medium power reactors, one may expect a further broadening of international collaboration for carrying out investigations at the above reactors with the aim of improving their infrastructures and their most effective use. Of the new projects, fairly attractive is the project of the 20 MW reactor in Garching (Munchen, Germany), which was designed with consideration of the ORPHEE reactor operational experience. The decision on [illegible] construction of this reactor may probably be adopted this year.

The situation of the modernization of the IR-8 reactor in the Kurchatov Institute (Moscow) is still uncertain. This reactor's rated power is also 20 MW for a thermal neutron flux density of 7×10^{14} n/cm^2/sec. In this reactor the high relative density of the neutron flux is ensured by the compactness of the core consisting of fuel element systems with a high multiplication coefficient and a low neutron migration length which provide for a high neutron output from the beryllium reflector.

In the USA the prospects for the development of reactor-based research is connected with upgrading the existing reactors and the Advanced Neutron Source Project (ANS)[8] in Oak Ridge. This is the heavy-water reactor project with a power of 350 MW and a thermal neutron flux of up to 10^{16} n/cm^2/sec. The new reactor would have the flux 10 times higher than the existing HFIR reactor in Oak Ridge, and 5-6 times higher than the HFR reactor in Grenoble. The ANS is a multipurpose reactor in its dedication. However, because of the high power and flux density it would be capable of serving over 1000 users a year. The project cost in 1992 prices was estimated as 1500 million US$. There are several other proposals for creating HFR (ILL)-type reactors and spallation pulsed sources for a power of 1 and 5 MW, respectively. Though all the above projects are in the stage of development, it is clear that in the nearest future, in the USA, the realization of new neutron source projects should begin, because the existing reactors were commissioned for operation in the mid-'60's.

In CANADA the concept of using international megafacilities and having one or two medium class reactors of their own prevails. Two projects are currently under consideration: modernization of the MNR reactor aimed at an increase in power to 12 MW, which would cost from 70 million to 120 million US$, and replacement of the NRU reactor in Chalk River by a new reactor for 20 MW, which would cost from 150 to 200 million US$.

In ASIA neutron research to a large extent will concentrate on the JRR-3M (Tokaimuri) and the DHRUVA (Bombay) reactors in the nearest future. As for new projects, in Japan, the projects for sources on the basis of accelerators are still under discussion.

In AUSTRALIA the plans for reconstruction of the existing reactor and the creation of a new source are being discussed.

In EGYPT the Atomic Energy Authority in Cairo has started work on the creation of the new 22 MW research reactor.

So, Europe, where in the '70's-'80's the greatest progress in reactor technology and experimental methods occurred, is the area most ready for transition to the next stage (beginning after the year 2000) of development of reactor neutron sources. Nevertheless, much effort would also be necessary to keep the process going. This is not only connected with technical and financial difficulties. The largest problem consists of the recently greatly increased fear of nuclear accidents and nuclear arms proliferation. A serious problem may be created by the USA adopted limitation for ^{235}U enrichment to be not higher than 20%. Because the USA is one of the main exporters of nuclear fuel, this would automatically lead to a decrease in power and, consequently, in neutron flux density at both existing and future reactors. Therefore, if the interested communities do not undertake active efforts, the prospects for reactors will be fairly modest.

6. Conclusions

The use of neutrons for physical research is so important that it finds more and more advocates, in spite of all difficulties: the increasing cost of operation of the existing reactors and the design and construction of new reactors, limitations on nuclear fuel, the resistance of the "Green Movement". The number of users of neutron beams, including reactor beams, is growing. According to the data reported to the Experts Meeting in Riso, the estimated total number of users was over 4000 in only the OECD countries in 1993, and it is expected to be about 7000 by the year 2000. In recent years Neutron Scattering Societies were organized in a number of countries: Australia, Canada, Italy, Japan, Switzerland, and the USA. In Germany the Neutron Society was organized by the Committee on Neutron Investigations under the Federal Ministry of Investigations and Technology, and in Russia by the Scientific Council of the National Program "Neutron Investigations of Matter" adopted by the Ministry of Science and Technical Policy of the Russian Federation this year. The issue of organizing the European Federation of Neutron Scattering Communities is presently under discussion. In this way the need of science for neutrons dictates the necessity of having a corresponding number of neutron sources.

At present nuclear reactors are the most widespread sources of neutrons for physical investigations, and we will still need them for a long time. The general tendency to develop spallation sources is driven by the strong desire to avoid possible nuclear accidents. In this respect, probably a less expensive linear proton booster, i.e., a powerful linear proton accelerator with a multiplying target, would be the most optimal source. Then, the operational experience of the IBR-type pulsing reactors would be of the greatest importance from the point of view of both the operation of multiplying targets and the development of experimental techniques for a pulsed source with a large neutron pulse width.

Neutron beam research is an example of "small-scale" science at large-scale facilities, where the typical research team consists of several leading scientists, post-graduates and students. The typical experiment goes on for a few days. Since one cannot get beam time for an experiment at a megafacility very often, e.g., applications at ILL for beam time are accepted only twice a year, the medium-class (10-20 MW) reactors for local use for the purposes of education and the preparation of experiments have specific significance. From the point of view of the general strategy it would be optimal to have two or three international centers on the basis of powerful specialized reactors of the HFR type (ILL) and a network of the ORPHEE-type reactors. In the ideal case the shutdown of reactors of the first and the second generations and the concentration of efforts on the most effective use of the existing reactors of the third generation and the construction of new would be most economical. However, real life does not allow us to do that, and therefore, it seems reasonable to support the existing projects and let the old reactors work for the service time that remains.

The greatest scientific and technical potential, together with experience in reactor design and construction, and the use of neutrons for physical research, has been acquired in the former USSR and the East European states. Therefore, support of the most promising projects with the participation of western scientists would answer the interests of the world community.

Today's large facilities are very expensive. The construction of a modern steady-state reactor costs several hundred million US$ at an annual operational cost on the order of several tens of millions US$. The conclusion is that the solution of all the problems of the construction of a reactor and its infrastructure, equipping an instrumentation base, organization of users' work, etc., is only possible by means of coordinated activities and international cooperation.

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Реакторные источники нейтронов

Рассмотрены состояние и перспективы реакторных источников нейтронов в мире для исследований в экспериментах по рассеянию. Обсуждаются области применения рассеяния нейтронов в сравнении с синхротронным излучением, этапы создания реакторов (с постоянным потоком и импульсных), их положение в настоящем и обозримом будущем в сравнении с источниками нейтронов на основе ускорителей.

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Aksenov V.L.

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Reactor Neutron Sources

The present status and the prospects for development of reactor neutron sources for neutron scattering research in the world are considered. The fields of application of neutron scattering relative to synchrotron radiation, the creation stages of reactors (steady state and pulsed) and their position in comparison with spallation neutron sources at present and in the foreseeable future are discussed.

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

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