объединенный
институт
ядерных
исследований
дубна

E3 - 12740

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Submitted to Int.Conf. on Nuclear Cross
Section for Technology, Knoxville, USA.

Лущиков В.И., и др. **E3 - 12740**

Некоторые направления программы исследований на ИБР-2

В обзоре приводятся параметры комплекса: импульсный реактор ИБР-2 + ускоритель-инжектор ЛИУ-30, данные о нейтронных пучках комплекса и их использование в некоторых, в том числе прикладных, исследованиях.

Сообщается программа первоочередных экспериментов по измерению $n\alpha$- и $n\gamma$ -сечений, сечений деления и нейтронных сечений для малонуклонных ядер. На примерах экспериментов с поляризованными нейтронами и некоторых других обсуждаются перспективы ядернофизических исследований с хорошим разрешением, которые откроются с вводом пучка ЛИУ-30 на неразмножающую мишень. Изложение иллюстрируется научными результатами, полученными в последнее время с использованием пучков импульсного реактора ИБР-30.

Препринт Объединенного института ядерных исследований. Дубна 1979

Luschikov V.I. et al. **E3 - 12740**

SELECTED TOPICS IN RESEARCH PROGRAM ON IBR-2

The physical start-up of the IBR-2 fast pulsed reactor took place in the Laboratory of Neutron Physics, JINR. Design values for an instantaneous thermal neutron fluxes are: 10^{17} cm^{-2} s^{-1} and 10^{16} cm^{-2}s^{-1} inside and from the surface of the moderator, respectively. In combination with the heavy current, short pulse injector (electron induction accelerator LIU-30 being under construction now) it will become a unique neutron source for the time-of-flight investigations in the energy range from 10^{-7} to 10^{6} eV. The characteristics of the complex IBR-2+LIU-30 are described. The neutron beams are numbered and their use in the condensed matter and applied research is mentioned. The program for the experiments on IBR-2 connected with $n\alpha$-, $n\gamma$ - and nf -cross section measurements as well as neutron cross section study for few nucleon systems are reported. The prospects for nuclear physics research on LIU-30 nonmultiplying target facility are outlined using as examples the experiments with polarized neutrons and nuclei and some others. The description is illustrated with the results obtained recently on the operating IBR-30 pulsed reactor.

Preprint of the Joint Institute for Nuclear Research. Dubna 1979

1. IBR-2 and LIU-30 complex - the high intensity pulsed neutron source.

1.1. Design characteristics. The periodically pulsed fast reactor IBR-2 with liquid coolant is constructed in the Laboratory of Neutron Physics, JINR. The physical start-up of IBR-2 was performed in the end of 1977- beginning 1978. Its operation at design power level is being prepared. The design mean and pulse thermal power is 4 MW and 7700 MW, respectively, pulse duration being 100 μsec and pulse repetition rate - 5 p.p.s. Total neutron yield from the active zone of a volume of 22 l is to be $1.7\times10^{17}s^{-1}$. The instantaneous thermal neutron flux within the moderators will reach $10^{17}cm^{-2}s^{-1}$ and that from their surface - $10^{16}cm^{-2}s^{-1}$. The latter exceeds the thermal neutron flux from moderator surfaces of best stationary reactors by a factor of 10. Several references, see for example, ref./1/ give details on the IBR-2 characteristics, its construction and operation. The IBR-2 reactor design is new if compared with the previous IBR reactors. Here we employ liquid sodium as a coolant. The reactivity modulation is performed with the help of the moving reflector instead of the rotating active core. The nuclear fuel is 90 kg of plutonium dioxide. The fuel rods are to be replaced once per 4 years period.

The IBR-2 reactor is also designed to operate as a dynamical multiplier of neutrons from the target of the electron induction accelerator LIU-30. Thus provided neutron pulses will be 50 times shorter. The accelerator is being constructed (electron energy 30 MeV, current 250 A in the pulse, pulse duration o.5 usec, beam power on a target 200 kW). The accelerator building 160 m long is built. The assembly works started of the electron gun and first module of LIU-30.

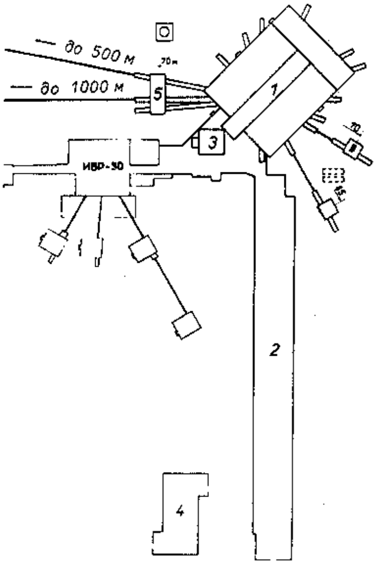


Fig.1. Arrangement of the buildings and flight tubes of the IBR-2 +LIU-30 complex.

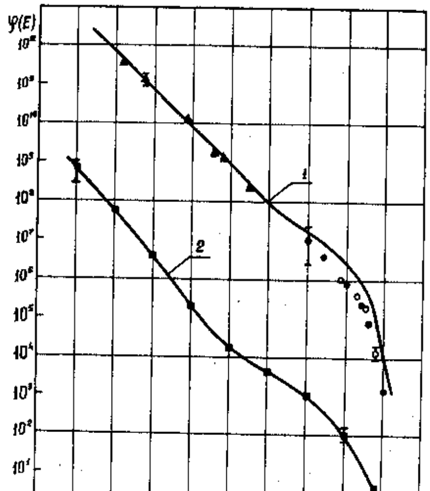


Fig.2. Spectra of neutrons from the surface of moderator (1) and in the external beam (2) at a distance of 8 mm from the reactor core (taken from ref./13/).
E - neutron energy in MeV
$\varphi(E)$ - neutron flux in $sm^{-2}sec^{-1}eV^{-1}$ per a power of 1 MW, channel diameter being 20 cm.

1.2. Source performances in different regimes. The IBR-2 reactor in combination with LIU-30 is to be a very powerful neutron source to serve the needs of scientists performing physical investigations with the time-of-flight technique. The arrangement of buildings and flight tubes of the whole complex is shown in Fig.1. The measuring pavilions and flight tubes from the IBR-30 reactor (in operation now) are planned to enter the arrangement. The nonmultiplying target of LIU-30 is to be placed instead of the IBR-30 core. This will allow to operate with short neutron and γ-ray pulses. The arrangement as a whole will include 20 beams, 14 of them being in the new experimental building with two halls 30 m x 60 m each.

The IBR-2 and LIU-30 complex is to perform in three modes:

- reactor mode (IBR-2), pulse duration ~ 100 μsec;
- dynamical booster mode (IBR-2+LIU-30), pulse duration 2 - 10 μsec;
- accelerator mode with nonmultiplying target (LIU-30), pulse duration 500 nsec at the beginning, and 50 nsec in the future.

Table 1

The characteristics of the complex IBR-2 + LIU-3 in three modes

Parameters	IBR-2	IBR-2 + LIU - 30		LIU-30	
1 Total neutron yield s^{-1}	1.7×10^{17}	6.6×10^{16}	1.2×10^{16}	6×10^{14}	6×10^{13}
2.Pulse duration μsec	100	10	2	0.500	0.050
3.Pulse repetition rate p.p.s.	5	50	50	50	50
4.Fast neutron flux (E > 10 keV) in the active core					
a)instantaneous $cm^{-2}s^{-1}$	6×10^{17}	2.2×10^{17}	2.0×10^{17}	-	-
b)average $cm^{-2}s^{-1}$	3×10^{14}	1.1×10^{14}	2.0×10^{13}	-	-
5.Resonance neutron flux ($E = 10^3$ eV) on the sample at resolution 0.1% $cm^{-2}s^{-1}$	-	-	0.4 (2000 m)	0.32 (500 m)	3.2 (50 m)
6.Thermal neutron flux from the moderator surface					
a) instant. $cm^{-2}s^{-1}$	1.0×10^{16}	3.9×10^{14}	7.2×10^{13}	-	-
b) average $cm^{-2}s^{-1}$	5.8×10^{12}	2.2×10^{12}	4.0×10^{11}	-	-

The neutron source characteristics for the above mentioned modes are given in Table 1. Line 5 in the Table presents the figures of merit at 1 keV, i.e.,the intensity of the 1 keV neutron beam on the sample 1 cm^2 with a fixed resolution of 0.1%. In the brackets the flight path to achieve this resolution is indicated. The first mode (IBR-2)is mainly planned for the experiments with thermal and epithermal neutrons. The second mode (IBR-2 + LIU-30) is expected to gain benefits in the experiments under moderate resolution in the energy region up to several hundreds eV. The third mode (LIU-30, pulse duration 50 nsec or less) is to have a higher figure of merit. It will provide means for neutron cross section measurements and other experiments under good resolution in the energy range $10^3 - 10^5$ eV.

1.3. Neutron characteristics measured during the physical start-up of IBR-2. On January 13, 1978 the IBR-2 reactor was started to operate in the pulse mode at a pulse repetition rate of 50 p.p.s. and 5 p.p.s. In February and March 1978 the reactor worked for 100 hrs at an average power of 500 W. The reactor parameters were investigated and are reported in refs./2,3/. The pulse duration was measured to be equal to 200 μsec instead of expected 100 μsec. Additional measurements showed the possibility to make the pulse shorter by improving the construction of the auxiliary moving reflector.

During the physical start-up the shape of neutron spectrum and neutron fluxes were measured/3/. Data on thermal neutron fluxes obtained by the activation method (gold and copper foils) proved the design value of the flux (Table 1) real. The results of measurements of the spectrum shape at $E > 1$ eV are shown in Fig.2. They were got by the technique of neutron spectra unfolding from readings of the activation thermal, resonance and threshold detectors. The spectrum in the resonance energy range $1 < E < 10^4$ eV should be E^{-x}, where $x \leq 1$. The smooth curve in Fig.2 does not obey this law (there x = 1.25). However these results should be regarded as qualitative due to considerable uncertainties of the method conventionally used for the dosimetry purposes. In planning the experiments it seems reasonable to use some modification of the empirical formula derived in ref./4/ for resonance neutron fluxes of the IBR-30 reactor:

$$N(E) = \frac{2.7 \times 10^9 \, W}{l^2 \; E^{0.9}} \quad cm^{-2} s^{-1} \, eV^{-1}$$

where W is the reactor power in MW and l is the flight path (reactor-detector) in m, E is the neutron energy in eV.

2. IBR-2 neutron beams in the future use

The arrangement within the experimental hall of 14 neutron beams of IBR-2 with spectrometers for the time-of-flight investigations is shown in Fig.3.Roman numerals indicate neutron beams. The spectrometers are given Russian denotions.

2.1. Neutron channel for the measurements of double differential cross sections.

The flight tube II terminates in the pavilion at a distance of 95 m from the reactor core. Here the spectrometer (DIN-2) with mechanical chopper is mounted by the Physics-Energy Institute (Obninsk, USSR)/5/. Two modifications of the spectrometer allow to study inelastc neutron scattering under moderate resolution with a monochromatic neutron beam up to $10^7 cm^{-2} s^{-1}$ on the sample and under highest possible resolution up to 10^{-7} eV at a neutron flux of $10^4 cm^{-2} s^{-1}$. The figure of merit of the spectrometer is better than that of other time-of-flight spectrometers by an order of magnitude and is comparable with the figure of merit of three-crystal spectrometers at high flux reactors. A broad program for investigations of quantum liquids and ideal crystals, as well as a program for applied research is developed.. The latter includes the double differential cross section measurements for the moderator materials of thermal reactors and thermal convertors of fast reactors in the temperature range 4 - 200 K.

2.2. Neutron channel for the experiments with ultracold neutrons.

Experiments with ultracold neutrons (UCN) are performed in the lowest energy part of the maxwellian spectrum, i.e., up to $E_{bound.} \sim 10^{-7}$ eV. Below $E_{bound.}$ neutrons are totaly reflected at any angle of incidence and may be kept in closed vessels. Since the UCN portion in the thermal spectrum is small, i.e.,about $\frac{1}{8} (V_{bound.}/V_{th})^4 \simeq 10^{-11}$, one needs high flux stationary or pulsed reactors to perform experiments with them. Several reviews, for example refs./6-8/, are devoted to these investigations started in 1968 in Dubna and Munich, and then at some European research centres. Recent issues of BNL-325 already contain data on the cross sections of neutrons at energies ranging from 10^{-4} to 10^{-7}eV. The experiments revealed some uncommon UCN properties and more are still under investigation. But at present the use of UCN for the neutron properties study (such as the the lifetime or electric dypole moment EDM) seem to be most interesting from the physical point of view. The search for EDM is directly connected with the T-violation problem in particle interactions. The so-called UCN confinement method for the EDM measurement proposed in ref./9/ was first employed in the Institute of Nuclear Physics of USSR Academy of Sciences (Gatchina). An upper EDM limit of 1.6×10^{-24} ecm/10/ was obtained.

In Dubna a facility "TRISTOM" is constructed to be used on the neutron channel III of the IBR-2 reactor. Its expected EDM sensitivity will be at a level of 10^{-25}ecm/11/. The neutron channal III is designed for the extraction and guiding of UCN. A hydrogen-containing convertor cooled down to 20 K is to be used as an UCN source together with the neutron shutter to increase the UCN density inside the chamber of the Ramsey type magnetic resonance spectrometer.

2.3. Beams for the condensed matter and applied investigations. Seven horizontal channels will be employed (i.e. IV - VIII, X, XI) in the time-of-flight experiments and three inclined ones (not shown in Fig.3) for neutron irradiation. Neutron beams IV,V,VI are to be equiped with a liquid hydrogen moderator at a maxwellian spectrum temperature of 50 K. Water moderators (their thickness can be varied from 35 to 55 mm) are mounted on other beams. The temperature of their maxwellian spectrum is 400 K. The program for condensed matter and biological research with the IBR-2 reactor is comprehensive, but, since it has no close connection with the topic of the present conference, it suffices to mention review papers /1,12/.

The following installations (Fig.3) are being constructed and partly built for the implementation of this program:

- spectrometer "ЧОК" (COK). To investigate by small angle diffusion neutron scattering the structure of biological crystals and macromolecules in solutions;

- spectrometer "КОРА" (CORA). To study inelastic thermal neutron scattering by the correlation time-of-flight spectroscopy method;
- diffractometers "БИО" (BIO). To perform neutron diffraction investigations on complex crystals. Apparatus "ИМУ" (IMU). To study the behaviour of the matter in pulsed magnetic fields by the time-of-flight diffraction method;

- spectrometers of inverted geometry "КДСОГ" (KDSOG), "СУНИ" (SUNI) with neutron monochromatization after scattering. To study the dynamics of organic crystals and energy levels of paramagnetic ions in crystals. The spectrometers will be installed at a distance of 100 m from the reactor and equipped with mirror neutron guides;

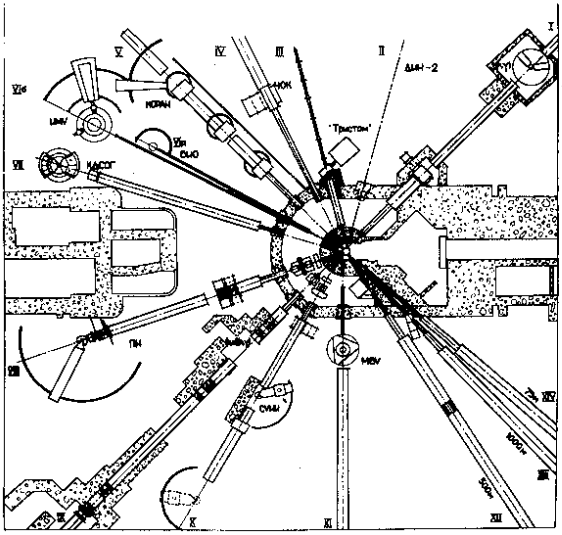
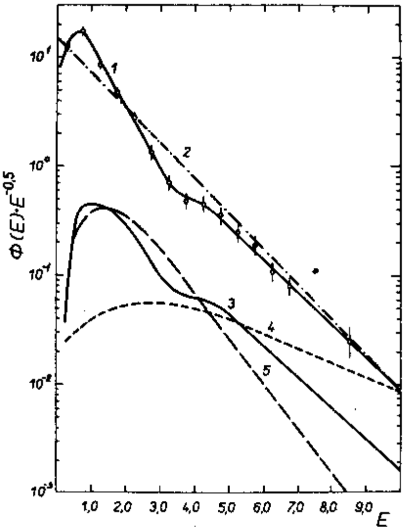


Fig. 3. Arrangement of neutron beams and spectrometers discussed in 2.3.

Fig.4. Formation of fast neutron spectra for the medical and biological research.

1. Nonfiltered spectrum from the IBR-30 channel.
2. Fission spectrum of ^{235}U fission induced by thermal neutrons.
3. Spectrum obtained with the $ZrH_{1.8}$ + +W filter.
4,5. Spectra from the berillium target on a cyclotron with deuteron current.



- spectrometer of polarized thermal neutrons "ПН" (PN) based on polarizing mirror neutron guides. Neutron beam will be polarized to 97% in the wavelength range 1 - 6 Å at a flux of 10^7 cm^{-2}s^{-1} on the sample ;

- apparatus "МБУ" (MBU) on the flight tube XI. To perform medical biological investigations with neutrons. This subject is a part of the topic of the present conference. As a preparative step the measurements of the characteristics of the specially designed neutron beam and some radiobiological research were carried out at the IBR-30 reactor. In Fig.4 from ref./13/ there are shown the conventional spectrum (1) and the spectrum (3) obtained after transmission of neutrons through the zirconium hydryde and tungsten filters 4 cm and 2.5 cm thick, respectively. The average energy of neutrons transmitted through the filter increased up to 3 MeV and became about that of neutrons (5) from the berilum target irradiated by deutons at an energy of E_d = 11 MeV. The radiation doses measured on IBR-30 at various filter thicknesses were 0.4 - 1 rad/min (neutrons) and 0.07 - 0.1 rad/min (γ-rays). For IBR-2 one expects to have up to 500 rad/min at a distance of 8 m. This will allow to achieve (using thicker filters) a more optimal average spectrum energy of 6 MeV. Such beam may serve for neutron diagnostics and maybe neutron therapy at reasonable doses of $\sim$ 50 rad/min. It is equivalent to berillium target at cyclotron with a current of 100 μA and deuteron energy of 15 MeV (curve 4).

Neutron flight tube XI will be also eqipped with a mirror neutron guide to perform element analysis by using capture γ-rays. It has advantages, if applied for the analysis of biological and other objects in comparison with activation method, since the intensity of sample irradiation decreases by a factor of 3 - 4 orders of magnitude. Maximal absolute sensnsitivity at a level of 10^{-9} g/l is expected for B, Gd, Sm.

In order to implement the materials research program the IBR-2 reactor will have three pneumotransport systems,so that samples 14 mm in diameter and up to 40 mm long could be irradiated. Pneumotransport channels are directed to the active core, reflector and moderator. The former provides a mean flux of 3.5×10^{14} cm^{-2}s-1 of fast neutrons with energies E=1.5 MeV, instantaneous neutron flux being 7×10^{17}cm^{-2}s^{-1}. The irradiated samples will be sent to hot chambers or directly to physical installations. High neutron fluxes from IBR-2 may serve the needs of scientists studying the kinetics of radiation damages characterized by the relaxation time within the 10^{-1} - 10^{-4} sec interval and of those making material research for fusion reactors.

The pneumotransport systems will be also used in the activation analysis by fast and thermal neutrons. The experience acquired at IBR-30 in the express method of activation analysis with Ge(Li) detector/14/ proves this field of applied research to be advantageous with the IBR-2 reactor also.

The same is true for the use of thermal neutron fluxes to study the distribution profiles of boron atoms in silicon and other materials. The detailed description of this method having high depth resolution is given in review/15/.

3. Nuclear Physics experiments

The IBR-2 reactor as a very powerful pulsed neutron source could be useful in the study of processes with very small neutron cross sections such as nα - n,$\gamma\alpha$ -, n,γf; etc. Long pulses are sometimes advantageous, since the instantaneous loading of detectors is lower and slow detectors and secondary-ray spectrometers with moderate responce times could be used.

3.1. Cross sections and spectra from nα -, n,$\gamma\alpha$ - and nγ-reactions. Nearly all experimental data on the structure of compound states (neutron resonances) available at present in the field of neutron spectroscopy contain mainly partial γ -widths of transitions to the ground or to a comparatively simple (fewquasiparticle) nuclear state. They give information only about the fewquasiparticle components of the wave function of compound states. The study of the probability of α-decay of neutron resonances and γ-transitions between nuclear compound states through (n, $\gamma\alpha$)reaction may provide information about manyparticle components of the wave function of high excited nuclear states. The investigation of γ-transitions to collective states also serves this aim.

The resonance α-widths for about a dozen and half nuclei with $65 < A < 178$/16,17/ were measured on the IBR-30 reactor. Experimental data obtained on average α-widths (Fig.5), on total α-widths and partial α-widths distributions (Fig.6) are well described in the frame of the statistical theory, the exceptions are the average α-widths of deformed nuclei and total α-widths distributions of J=4 resobances in ^{149}Sm. The amount of helium produced in some materials due to the (n, α) reaction was also estimated/18/. Experimental data on $\Gamma_{\gamma\alpha}$ in resonances with different spins obtained in the study of the two-step (n, $\gamma\alpha$) process gave indication of the interesting phenomenon: the prevalence

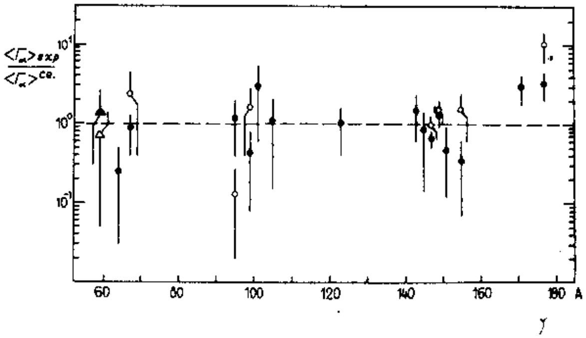


Fig. 5. Comparison of experimental average α-widths with theoretical ones in dependence on the nuclear mass number.

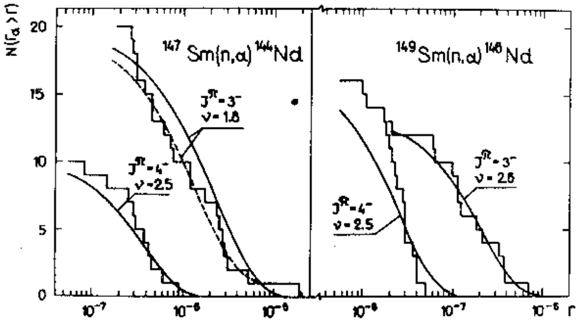


Fig. 6. Distribution of partial widths of α-decay of the compound states of ^{144}Nd and ^{146}Nd with different spin J.

Hystograms - experiment;

solid lines - theory.

of M1 transitions between the compound states[19]. They are the transitions from the 55 eV resonance to the states shown in Fig.7 by dotted lines. However, to be sure about the above-mentioned prevalence one should perform the statistically more precise measurements of $\Gamma_{\gamma\alpha}$. Such experiment on the 55.3 resonance of ^{143}Nd is among the first ones included in the program of experiments on the IBR-2 reactor.

Since $\Gamma_{\gamma\alpha}$ -width in the (n, $\gamma\alpha$) process scarcely changes from resonance to resonance with same spin (due to averaging over many intermediate states), the experiment may be made on 2 - 3 resonances, if high neutron fluxes were available.

The program for experiments on IBR-2 includes also the measurement of the ^{7}Be(n,2α) reaction cross section in the thermal and epithermal neutron energy range to investigate the parity conservation of nuclear forces[20]. The cross section of the reaction must be small due to parity selection rules. Besides,the target may contain a small (10^3 - 10^4 less than usual) number of nuclei, since berillium-7 is radioactive ($T_{1/2}$= 53.6 days). So, a very powerful neutron source is absolutely necessary.

The IBR-2 reactor will allow to perform more complicate experiments than those with IBR-30. For example, the investigation of α-γ angular correlations in the decay of ^{150}Sm compound states is planned. It will provide information about the contribution of partial α-transitions with different orbital momenta.

With the employment of IBR-2 in combination with LIU-30 the broader range of nuclei could be covered in the study of neutron resonance α-decay in order to explain why the cluster and optical model[17] did not describe satisfactorily the average α -widths of deformed nuclei. Furhter experiements to measure the (n, α) reaction yield will be made for some materials used in the construction of the reactors.

The gamma-ray studies in (n, γ) reaction carried out in recent years revealed some deviations from the statistical theory in the description of the decay of highly excited[21] states. That is important for understanding the fragmentation of simple excitations over compound states. The IBR-2 + LIU-30 complex will be used in the study of the regularities in the population of nuclear states having definite structure, for example, octupole states with spin 3^- and others.

The study of gamma-cascades in γ-decay of compound states will be continued. That means performing the measurements of the fluctuations (from resonance to resonance) in the population of low-lying states. They are intended to clari-

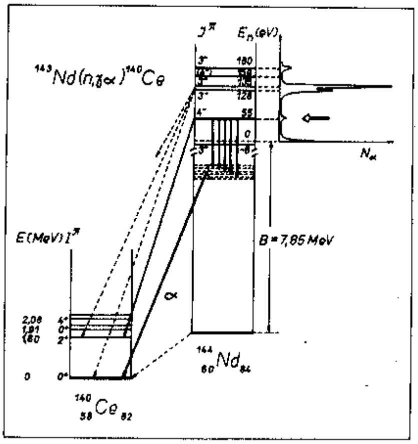


Fig. 7. Scheme for the (n, γα) process in ^{143}Nd.

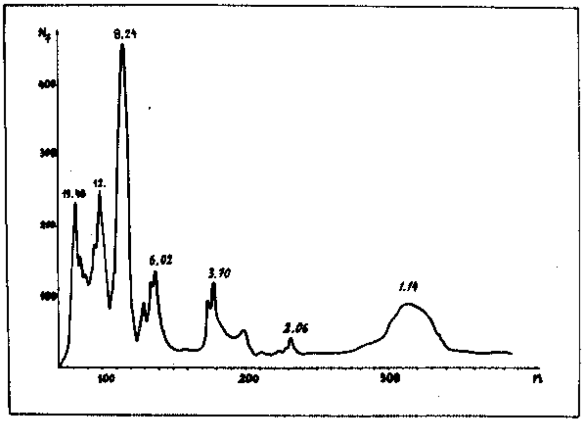


Fig. 8. Time-of-flight resonance spectrum obtained during 10 hrs. of measurement with the ^{235}U target and fission fragments Si-detector, the flight path being 75 m, in IBR-30 reactor mode of operation.

fy the reason for the different behaviour of population fluctuations in a region of $A \sim 100$ (spherical nuclei, s-neutrons strength function S_o being minimal) and of $A \sim 150$ (deformed and transition nuclei, maximum S_o)[22].

This part of the program on IBR-2 foresees the use of the flight tubes I and IX (tangential flight tube). In order to investigate the average parameters of interaction of neutrons with nuclei, there will be installed Fe- (E=24 keV) and Sc- (E= 2 keV) filters on the beams. The background conditions with filtered beams on pulsed reactor may be improved by a factor of 2-3 orders of magnitude using the time-of-flight technique as compared with the stationary reactor facilities. The calculated intensity of the filtered beams on the fast neutron pulse reactor IBR-2 is equivalent to that from the thermal neutron stationary reactor with a power of $W \sim 50$ MW.

3.2. Fission cross sections. Fission process study is being carried out in the Laboratory of Neutron Physics for several years. It will be continued with the IBR-2 + LIU-30 complex. The study goes in two directions. The first is the multiparameter measurement of slow-neutron-induced fission cross sections, i.e.,the joint measurements of the kinetical energies of fission fragments, of the instantaneous γ-rays and neutron multiplicities and of the mass distribution of fragments. This will also serve to further improvement of nuclear data necessary for reactor calculations. The comparison of the above-mentioned data for many resonances is interesting from the point of view of finding the spin dependence of different characteristics of fission and their correlations. Presently available data are not unambiguous,because the variations of the above characteristics from resonance to resonance, if present, are about 1% or even less. So, the success of the experiments strongly depends on the intensity of neutron beams especially in the case of coincident events in different channels of the fission reaction. As is seen from the spectrum in Fig.8 (the results obtained using solid states fission fragments detector in ref.[23]) the IBR-2 reactor even at the first step of operation may provide sufficient intensities for such experiments, though not optimal resolution.

The study of the $(n, \gamma f)$ process, i.e., the process of fission after the emission of γ-quanta, is closely connected with the above. The possibility of its existence and calculation of its cross section are reported in refs.[24, 25]. The process was searched for (see review papers[2,6]) by measuring the correlation of the multiplicity of fission γ-quanta, average number of neutrons per fission ν and resonance fission widths f. However, all data obtained represent only indirect experimental evidence. The direct method for the search of the $(n, \gamma f)$ process was developed in Dubna[27]. It is based on the registration of the X-ray quanta emitted as a result of the internal conversion of γ-quanta preceeding fission and detected in coincidence with a fission event. In Fig.9

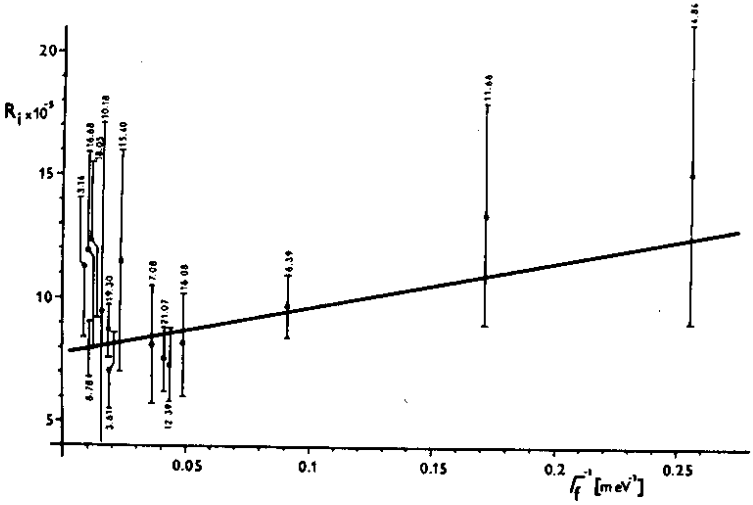


Fig. 9. Results of the (n, γ f) process study on ^{235}U during 260 hrs. of measuring time with the IBR-30 in booster mode of operation.

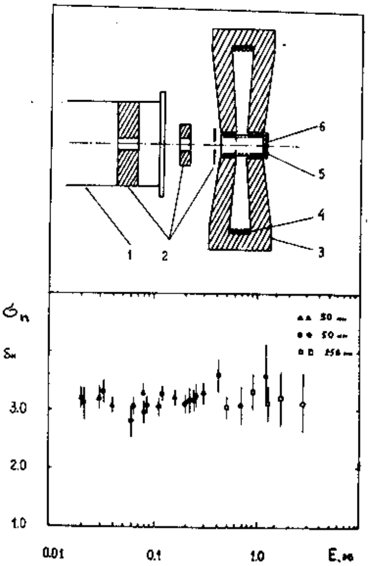


Fig. 10. Experimental lay-out and results obtained for the scattering cross section $\sigma_n(^3He)$ (b) in dependence on neutron energy E (eV).

one may see the results obtained in ref./27/. The dependence of the X-ray yield per fission event R on resonance fission widths Γ_f is shown. Since R is proportional to $\Gamma_{\gamma f}$ and the latter (similarly to $\Gamma_{\gamma\alpha}$ under consideration in 3.1) scarcely depends on resonance characteristics, the relative contribution of the (n, γ f) process must decrease with increasing Γ_f . It seems may take place (the obtained result $\Gamma_{\gamma f} = 2.1^{+1.5}_{-1.7}$ meV), though, to be sure, one must acquire more data.

The second direction in the measurement of fission cross sections at JINR is connected with nuclear data needs for fast neutron reactor calculations. For several years already the Laboratory of Neutron Physics (Dubna) jointly with the Physics-Energy Institute (Obninsk) perform experiemnts in this field. They include the measurement of transmission functions and self-indication ratios for ^{235}U, ^{238}U, ^{239}Pu and the calculation on their basis of average group cross sections and resonance self-shielding factors./28/ The former performed for a wide range of sample thicknesses at energies from several eV to dozens keV give inforamtion about the self-shielding effects in cross sections that could not be obtained by even very precise high resolution cross section measurements made in a limited range of sample thicknesses. Recent ^{235}U and ^{239}Pu results are given in paper /29/ contributed to the present conference. The work is to be continued with the IBR-2 + LIU-30 complex.

3.3. Precise (n n)- and (n γ)-cross section measurements in the few nucleon systems. The experimental study of the few body problem was initiated on the IBR reactor in 1966 with polarization experiments on an unambiguous choice of (n d) scattering lengths./30/ Recent measurements performed with the IBR-30 reactor contributed much to this research. Since the theory of few nucleon systems now attends to nuclei consisting of four nucleons, it is interesting to measure (n^{3}He) scattering lengths. Experimental lengths may in principle be obtained from a combination of data on total and coherent scattering cross sections. But the experiment is difficult due to the competing (n,p) absorption process having a large cross section of 5400 b.

The results first obtained in/31/ for the total cross section $\sigma_n(^3He)$ are shown in Fig.10.

Different points are taken at various pressures of the ^{3}He-gas in the target (minimal 30 mm Hg) and under different conditions. Fig.11 presents the whole data on the basis of which one may (by the graphical method) obtain the scattering lengths discussed in ref./32/. Crosses indicate theoretical results obtained by V.F.Kharchenko/41/ with different nucleon-nucleon potentials. As is seen one needs to lessen the uncertainty of data on scattering cross section σ_n ,and incoherent scattering cross section σ_{inc} available up to now only by the indirect method. The accuracy of σ_n and σ_{inc} is worse than that of the recently obtained co-

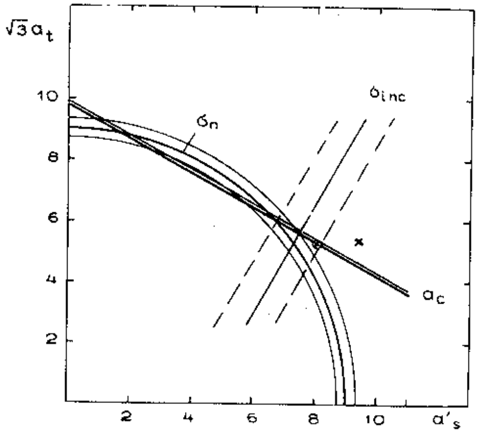


Fig.11. Data for obtaining the triplet a_t and real part of the singlet a'_s components of scattering lengths in n^{3}He scattering.

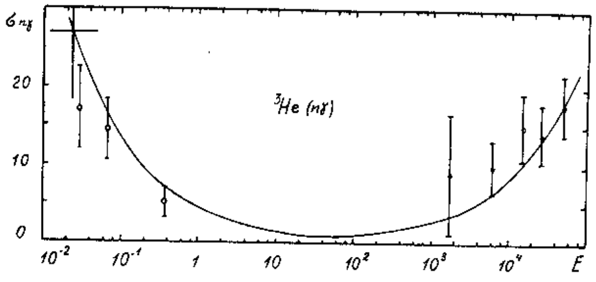


Fig.12. Neutron radiative capture cross section by ^{3}He (μb) in dependence on neutron energy (eV).

herent scattering length result a_c [33]. The IBR-2 reactor will bring a possibility for more precise measurements of σ_n and of the direct measurement of σ_{inc} using polarized gaseous ^{3}He target.

The study of radiative neutron capture in ^{3}He is closely connected with the four-nucleon problem, though up to now remained practically unattended both experimentally and theoretically. The results obtained this year in Dubna are shown in Fig.12 [34]. The accuracy is not high, but from the qualitative behaviour of the energy dependence one may conclude that at low energies the capture process is of the s-wave nature, while at higher energies - p-wave. The calculation of thermal cross section (M1 transition) were performed taking into account only s-states of ^{3}He and ^{4}He described with the simplest (gaussian) wave functions. The comparison of experimental and theoretical results allowed to estimate an admixture of the "mixed symmetry" state of o.14% in ^{4}He. Theoretical results become multi-meaning, if the D-component of the ^{3}He, ^{4}He ground states and various meson exchange currents [35] are taken into account. Thus, to have a reliable theory one should perform more precise measurements of thermal cross section $\sigma_{n\gamma}$ (^{3}He). They are included in the program of experiments on IBR-2.

Precise measurements of.the D(n γ) radiation capture cross sections are also interesting from the point of view of meson exchnage currents as well as of their importance for the reactor calculations. The first stage of measurements is reported in ref. [36] contributed to the present conference. Further measurements are included in the IBR-2 reactor research program. Then it will be possible to carry out a polarization experiment to determine separately the doublet and quartet component of the D(n γ) reaction cross section.

3.4. Prospects for some other experiments after the start of LIU-30. The ptoblem of the spin dependence of neutron cross section is under discussion for a long time already, but its experimental investigation encounters many methodical difficulties. The apparatus for the measurement of the total cross section of polarized neutrons with polarized nuclei installed at IBR-30 is shown in Fig.13. Its principal components are: the polarized proton target (4) as a neutron polarizer and the ^{3}He/^{4}He refrigerator (5) at a temperature down to 0.03 K for nuclear polarization. The method for the polarization of neutrons via transmission through the polarized proton target was developed in Dubna and then used in the Los Alamos and Oak Ridge Laboratories to measure the spins of resonances of fissionable nuclei [37]. In Dubna the rare earth nuclei were mainly investigated in the neutron transmission experiments [38]. As is seen from Fig. 14 the nuclei investigated behave quite differently. This is difficult to explain with the introduction of the spin-dependent optical potential. Most probably the cross sections intermediate structure connected with spin value is responcible for that. For the further investigation of the problem one needs to

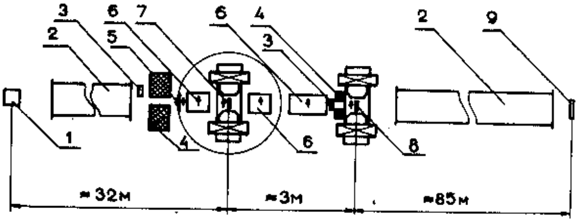


Fig.13. Apparatus for measuring total cross sections of polarized neutrons with polarized nuclei.

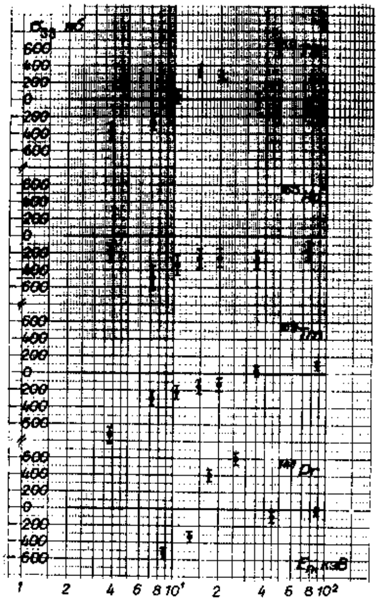


Fig.14. Data on the spin-spin cross section σ_{ss} via neutron energy E for a number of rare earth nuclei.

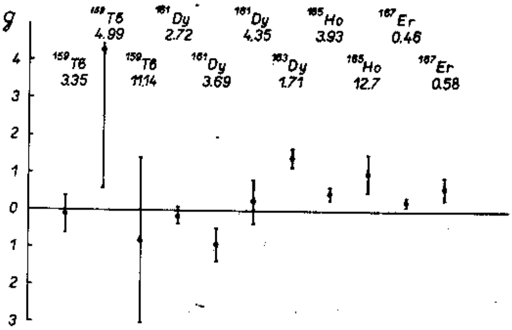


Fig.15. Gyromagnetic ratios (g-factors) of neutron resonances in a number of nuclei obtained in the experiments with polarized nuclei.

perform the polarization measurements of partial neutron cross sections (scattering and capture cross sections). This will be possible in principle with the LIU-30 facility working in the regime of nonmultiplying target. As for the spin dependence of the neutron strength functions the Dubna-results show its not exceeding 10 - 15 % (if at all present) for the nuclei investigated.

The same $^3He/^4He$ refrigerator was used for the measurement of magnetic moments of neutron resonances. They were the first systematical investigations of that kind. The results are reported in ref./39/ and shown in Fig. 15. They reveal the collective properties of nuclear high excited states in agreement with theoretical predictions within the thermodynamical approach. The experiments planned for the IBR-2 + LIU-30 are aimed at further enlargement of the number of resonances under investigation in a nucleus and of the number of nuclei.

In the nearest future it seems possible to obtain the new inforamtion about the deformation of nuclei excited to about neutron binding energy. Some experiments were done recently in Dubna/40/ with an attempt to measure the variation of the mean square nuclear radius after excitation. The method of the isomeric shift of the neutron resonance was proposed and used. The shift ΔE between the resonance energies appearing in different chemical compounds may occur due to hyperfine interaction of the atom electrons with nuclear charge z. It is described by the formula

$$\Delta E = \frac{2\pi}{3} e^2 \cdot z \cdot \Delta |\psi_{(0)}|^2 \cdot \Delta \langle R^2 \rangle ,$$

where $\Delta |\psi_{(0)}|^2$ is the difference in the electron densities on the nucleus between a pair of chemical compounds investigated. Theoretical prediction gives $\Delta \langle R^2 \rangle \approx$ ≈ -0.1 fm which leads to a small, but detectable resonance shift of $10^{-3} \cdot \Gamma$. The preliminary experimental result is $\Delta \langle R^2 \rangle = (-0.6 \pm 0.3)$ fm /40/. The measurements are performed with IBR-30. Their extension is planned for the complex IBR-2 + LIU-30.

4. Conclusions

In the present paper some trends of future investigation with IBR-2, mostly in the field of nuclear physics are reviewed. They include the neutron cross section measurements important both in the study of nuclear structure and in the determination of nuclear constants needed for reactor calculations. Applied fields of research with IBR-2 are outlined also. At the same time the review does not practically cover the investigation of condensed matters, though more than 50% of the experimental program for IBR-2 is devoted to them. The research program developed for the IBR-2 and LIU 30 facilities has the following principle directions:

- investigations in the field of condensed matters and molecular biology;
- studies of fundamental properties of the neutron;
- neutron cross section measurement for the study of highly excited states and nuclear reactions and for applied purposes;
- applied research by using nuclear methods.

In the first step of the IBR-2 operation (regime IBR-2) the investigations of condensed matters will prevail due to rather long times of pulse duration. However, the measurements of $(n\,\alpha)$, $(n\,\gamma)$, $(n, \gamma\alpha)$, $(n\,n)$, $(n\,f)$ cross sections not requiring good resolution will be also done. The operation of IBR-2 in combination with LIU-30 (IBR-2 + LIU-30 regime) will allow to employ shorter pulses more suitable for nuclear experiments. Further shortening of the pulse duration to 500 nsec - 50 nsec (LIU-3 nonmultiplying target regime) will give a possibility of neutron cross section measurements at neutron energies up to 10^5 - 10^6 eV and other experiments under good energy resolution.

The IBR-2 start-up at full power will give birth to a new generation of high intensity pulsed neutron sources. The need in such sources is now commonly agreed. The neutron fluxes of stationary reactors approached their technical and financial limits. The new generation of neutron sources will include together with the IBR-2 reactor the new facilities on proton accelerators being designed or constructed. The IPNS (Argon Lab.) and SNS (Rutherford Lab.) facilities are planned for the condensed matter experiments with thermal and epithermal neutrons and the WNR source (with a coming storage ring) at the meson factory LAMPF to be used for nuclear investigations in a wide energy range.

The outlined possibilities for physical investigations with IBR-2 and LIU-30 are extensive, however the experience of the pulse reactor IBR-30 operation proves them possible. The present paper is devoted to selected topics in the experimental program proposed for the IBR-2 reactor. Needs and pressures in the future, as well as furhter experience may influence,of course,the actual research program on IBR-2.

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Received by Publishing Department
on August 16, 1979