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REVIEWS

Small-Angle Neutron Scattering at the Pulsed Reactor IBR-2: Current Status and Prospects

A. I. Kuklin[a,b,*], O. I. Ivankov[a,b,c], A. V. Rogachev[a,b], D. V. Soloviov[a,b,c], A. Kh. Islamov[a], V. V. Skoi[a,b], Yu. S. Kovalev[a,b], A. V. Vlasov[a,b,d], Yu. L. Ryzykau[a,b], A. G. Soloviev[a], N. Kucerka[a], and V. I. Gordeliy[b,e,f]

[a] *Joint Institute for Nuclear Research, Dubna, Moscow oblast, 141980 Russia*
[b] *Moscow Institute of Physics and Technology, Dolgoprudny, Moscow oblast, 141701 Russia*
[c] *Institute for Safety Problems of Nuclear Power Plants, National Academy of Sciences of Ukraine, Chernobyl, 07270 Ukraine*
[d] *Institute of Crystallography, RWTH Aachen University, Aachen, 52056 Germany*
[e] *Jülich Centre for Structural Biology, Forschungszentrum, Jülich, 52425 Germany*
[f] *Institut de Biologie Structurale Jean-Pierre Ebel, Université Grenoble Alpes—Commissariat à l'Energie Atomique et aux Energies Alternatives—CNRS, Grenoble, 38044 France*
**e-mail: kuklin@nf.jinr.ru*

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Abstract—Neutron diffraction studies on the small-angle neutron spectrometer YuMO (Joint Institute for Nuclear Research, Dubna), based on the IBR-2 pulsed reactor, have been reviewed. The main parameters of small-angle spectrometers, based on the time-of-flight technique, are considered. It is shown that the flux on sample is the key parameter of the spectrometers based on pulsed sources, which makes it possible (along with application of a multidetector system) to expand the dynamic range of scattering vector magnitudes. The history of the setting up of the first small-angle instrument based on pulsed sources is overviewed. The directions of development of small-angle spectrometers are shown. The results of YuMO studies in the fields of polymers, biology, materials science, and physical chemistry are briefly reviewed. The main strategies of development of small-angle neutron scattering on pulsed sources are considered. The possibilities of the small-angle instruments based on a synchrotron source and on a neutron pulsed source are compared.

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INTRODUCTION

Study of supramolecular objects has become especially urgent in view of the active development, in particular, various biological and nanotechnological scientific problems [1–9]. One can also expect manifestation of size effects on the scale of supramolecular structures [1, 10].

The quantitative characteristic of the structure of nanodispersed objects is a basis for understanding their properties and principles of operation. Correspondingly, the requirements imposed on the methods for nanoscale study of materials become more stringent. Along with conventional optical microscopy, the methods for studying small (from several angstroms to several thousand angstroms) objects include also the following high-power methods of electron microscopy: transmission electron microscopy, scanning electron microscopy, scanning transmission electron microscopy, and atomic force microscopy (AFM). Despite their great potential, these local methods are complementary to small-angle neutron scattering (SANS) and small-angle X-ray scattering (SAXS).

Being an efficient method for studying fundamental problems and solving most important technological problems, SANS is a popular technique for studying the supra-atomic structure of materials [11–15].

One of the most important features of SAXS is the possibility for analyzing structures of disordered systems [16, 17]. The method is used in condensed-matter physics, physico-chemistry of dispersed systems [18–20], surfactant aggregates [21, 22], biophysics and molecular biology [23–40], study of polymer

materials [41–44], and other fields of science and technology [6, 45–52].

This wide application spectrum is related, in particular, to the fact that SANS has some important features distinguishing it from SAXS. These distinctions are primarily determined by the general features of interaction of thermal neutrons with matter: large depth of penetration into material and the dependence of scattering on the isotopic composition of material and its magnetic properties, which makes SANS an irreplaceable method for structural studies. The fact that the neutron scattering lengths for hydrogen and deuterium differ to a great extent and the possibility for specific deuteration of macromolecules and supramolecular structures make SANS an irreplaceable tool for studying biological [9, 53, 54], polymer [55–57], and colloidal objects [58–62] and even for separating magnetic and nuclear components of magnetic fluids [63].

The purpose of this study was to consider the specific features of SANS and the historical aspects and prospects of this method in the foreseeable future.

1. BRIEF HISTORICAL OVERVIEW

A book devoted to the 50th anniversary of neutron discovery was published in 1983 [64], where I.M. Frank mentioned "small-angle diffraction method" in the section "Half a Century of Neutron Physics" and paid attention to the study of protein molecules and application of contrast-variation method to living objects.

The first in the world SANS system was implemented at the Institut Laue–Langevin (ILL), and the first time-of-flight (TOF) system based on pulsed sources was put into operation on the reactor IBR-30 [65] and then on the high-flux pulsed reactor IBR-2 by Ostanevich et al. [66].

The first SAXS spectrometer (based on a pulsed reactor) was installed in the fifth channel of the IBR-30 reactor. The small-angle spectrometer had a slit collimation, and proportional counters of the NW1-52 type (oriented vertically in the plane perpendicular to the beam) were used as detectors. It is noteworthy that the central part of the detection plane, through which the forward beam passed, was free of counters and structural materials. This design (the concept of forward-beam transmission was implemented later on the IBR-2 reactor) made it possible to reduce significantly the forward-beam background in the detector zone.

A further step in the development of small-angle spectrometers was the formation of a SANS system located in the fourth channel of the IBR-2 reactor [67]. This system has unique characteristics, geometry, and design features. In particular, its geometry is axially symmetric, the detectors have holes in the central parts for forward beam transmission, and a standard scatterer (metallic vanadium) is located before the detector in order to carry out regular absolute calibration of the scattering cross-section during sample measurements with a systematic error of no more than 10%.

Undoubtedly, the multidetector system [68, 69] was a breakthrough direction in the development of SAXS technique. This concept and method were proposed and implemented on the fourth channel of the IBR-2 and repeated afterwards (with some variations) on many small-angle systems: at the European Spallation Source, in which a conical detector was proposed to collect all neutrons [70]; at the ILL, based on the stationary reactor and using four choppers in various combinations and near- and far-field detectors [71]; and on the OPAL reactor of similar design in Australia [72].

Before 1999, the implementation of a multidetector system on the SANS spectrometer YuMO was hindered by the peculiarity of data-normalization system [67]. Nevertheless, both the absolute scale of scattering intensity and possibility for normalizing the data to the vanadium standard could be retained [69].

Despite the fact that the spectrometer was significantly upgraded later, the concepts that were laid in the basis of its design and implemented during several decades of its operation are still useful in physics, chemistry, molecular biology, biophysics, and materials science. To date, the application of contrast-variation method for living objects (as was mentioned by Frank) has been implemented on the fourth channel, even for protein complexes rather than individual molecules [31–33, 36, 39, 73].

2. ON THE COMPETITION AND COMPLEMENTARITY OF SANS, SAXS, AND MICROSCOPY

The specific features of these three methods were noted in the Introduction. To estimate adequately the trends in their development and future prospects, their advantages and drawbacks must be formulated once again. The main results of such comparison are listed in Table 1.

It follows from Table 1 that the question about applicability of a particular method depends on the specific problem. The second conclusion that can be drawn based on Table 1 is that these methods are complementary [19, 74, 75].

For example, Frank stated that "neutron diffraction (including small-angle) supplements in many respects other research methods. Therefore, the combination of neutron and X-ray diffraction (XRD) methods and electron microscopy is especially promising" [64]. Finally, an expansion of the list in the microscopy section can hardly change the contents and importance of the sections where small-angle instruments based on neutron and X-ray scattering are described. SAXS will always has an application scope

Table 1. Comparison of three main structural methods as applied to different materials

Parameter	SANS	SAXS	Microscopy
Character of observation	Integral	Integral	Local
Object sizes	10–1000 Å	10–1000 Å	From about 1 Å to 1 mm
Space type	Reciprocal	Reciprocal	Real (reciprocal)
Observation region	Volume	Volume	Surface, particles on surface, cut, cleavage of internal part
Range of applicability	Liquid, solid, and gaseous objects with good contrast	Liquid, solid, and gaseous objects with high electron density	Mainly solid, frozen, and liquid objects
Parameters that can be obtained	Shape and average size of particles in the matrix, parameters and type of size distribution, density in a particle, parameters of structural organization, molecular weight, aggregation number, persistent length, thicknesses of layers, fractal dimension, and mosaicity	Shape and average size of particles in the matrix, parameters and type of size distribution, parameters of structural organization, molecular weight, aggregation number, persistent length, thicknesses of layers, fractal dimension, and mosaicity	Size and shape of particles in real space and size distribution after treatment of a significant object area
Specific features	Contrast is formed by the nuclear density between the matrix and globules (object)	Contrast is formed by the electron density	Contrast is formed by the electron density and electron, X-ray, and light reflecting abilities
Drawbacks	Ambiguous interpretation, methodical complexity, low sensitivity, and low resolution	Ambiguous interpretation, methodical complexity, low sensitivity, and low resolution	Surface properties of objects, locality, and reconstruction of the 3D form using complex mathematical methods
Advantages	Contrast variation, deep penetration into material, "softness" with respect to biological and polymer objects, and possibility for studying magnetic structures	High data accumulation rate, availability, and relatively low cost	Clearness, comparative inambiguity of interpreting data obtained, and reconstruction of the 3D form

that cannot be covered by other structural methods (it will be considered below). XRD analysis and nuclear-magnetic resonance (NMR) are absent in Table 1. Undoubtedly, XRD analysis (especially implemented on the synchrotron sources of the last generation and the so-called X-ray free-electron lasers) yields breakthrough results [76–79]. NMR, in turn, is complementary to SAXS and allows one to solve many structural problems for small molecules [80].

3. DEVELOPMENT OF THE METHOD ON PULSED SOURCES

During few decades after publishing the classical study by Guinier [81] the methods for processing experimental data have changed drastically. A transition was made from processing SAXS spectra in the Guinier or Porod mode (treatment of a part of scattering curve, where the main results were the radius of gyration and Porod invariant) to fitting the total scattering curve using form factors of different models. The requirements to the measured scattering curve became even more stringent after the development of a radically new software package by Svergun et al. [82, 83]: the curve should be measured in a maximally wide range of momentum transfers. This range can be expanded by increasing the detector sizes and moving the detector along the neutron-beam axis. The drawback of this solution for expanding the range of the momentum transfers is the introduction of additional distortions (changes in the intensity, background, and the sample itself) into scattering curves, which will require correction when combining these curves. Therefore, in many small-angle neutron experiments, it is of crucial importance for the so-called dynamic range of momentum transfers (the ratio of the maximum and minimum simultaneously recorded vector **q**) to be maximally wide.

As was noted above, the application of a multidetector system is an alternative to broadening the momentum-transfer range (including the dynamic one). The proposed version of simultaneous use of two detectors [68, 69], which was implemented on the small-angle spectrometer YuMO based on the IBR-2 reactor, makes it possible to shorten significantly the experiment duration. Thus, to date, experimenter's task is to obtain data in a wide range of momentum transfers pulse with an acceptable statistical error, which is generally determined by the measurement time. The measurement time, in turn, depends on the scattering cross-section of the sample.

The key parameters of any small-angle system are the values of fluence and flux on the sample. Due to this, experiments can be performed with a small amount of sample, which may be critical for biological samples. Undoubtedly, the existence of lower scattering level, related to incoherent and inelastic scattering from the sample, limits the lower boundary of the scale of differential scattering cross-sections. However, an experience has shown that the coherent component (useful signal) can be selected at signal-to-noise ratio of up to 0.1 [84].

Obviously, this boundary is determined primarily by the statistical data-accumulation error (which is directly proportional to the detector count), while the detector count is directly proportional to the flux. Therefore, the question of measuring samples with a small scattering cross-section is determined ultimately by the flux (fluence) and background component (including the instrumental background). The peak power of the IBR-2 reactor exceeds the average power by a factor of almost 1000, which makes it possible to carry out measurements accurate to several thousandths of inverse centimeter per steradian. The use of the technique of SANS curve smoothing allows to figure out the momentum-transfer range [85, 86].

Almost all systems based on stationary reactors and pulsed sources are mounted in channels with cold moderators. The pulsed character of operation and the presence of reactor background (several percent in terms of power) are other specific features of pulsed reactors. Due to them, the flux on the sample decreases by more than half with respect to that of a comb-shaped water moderator; therefore, the signal/background ratio is deteriorated. Many experiments (especially biological with a small amount of sample) become impossible. The high quality of the YuMO spectrometer as a fast-acting system is thus lost [87].

Note that it is expected to obtain a fluence up to 10^9 n/(s cm^2) using a small-angle instrument based on the ESS-LOKI pulsed source at the source–sample distance of 23.5 m and maximum distance to the detector of 10 m. Four choppers will be used (two pairs with frequencies of 14 and 7 Hz). The dynamic momentum-transfer range is no less than 1000. It is planned to use boron-based detectors in grazing geometry along the perimeter of the detector volume [70].

Another line of research determining the future of small-angle instruments is broadening of possibilities of affecting the sample. Indeed, subjecting a sample to pressure with controlling temperature and volume in an aqueous medium [88–92], applying magnetic [93, 94] or electric [95] fields, exposing a sample to laser or light illumination [96, 97], and investigating kinetics [38], one can obtain new qualitative knowledge about the processes of structural changes under the aforementioned factors.

There is a factor hindering the interpretation of a supramolecular structure using the SAXS method: its polydispersity. On the one hand, almost all nanoscale products are polydisperse (the obtainment of monodisperse objects can be considered as a new industrial breakthrough). On the other hand, biological objects (proteins, complexes) should be monodisperse proceeding from their existence conditions; however, protein dimers and oligomers are formed even in the low-concentration form. This situation hinders the formation of low-resolution structures. This factor can be partially suppressed using the technique of approximating at zero concentration [98].

For biological samples, this problem can be solved using simultaneously chromatography and small-angle measurements [99, 100]. Such results were obtained on the BM29 synchrotron specialized system [101].

It was a new fundamental step in the development of the SANS method. The first test experiments aimed at estimating the possibilities of these measurements on the YuMO system were carried out in [102], but for only a comb-shaped waster moderator.

It was shown in the 1980s that there are samples for which the SANS curve is a straight line on the double logarithmic scale. For example, it was shown that the power law indicates fractal nanoscale organization of the sample [103–105]. Strictly speaking, fractals can be referred to as mathematically definite objects (the so-called deterministic fractals). The theoretical SANS curves for deterministic fractals were described and calculated in [106–112]. It was also shown in those studies that additional parameters (primarily, the iteration number [108]) can be found from the SANS curve.

4. FACTORS DETERMINING THE EXPOSURE TIME

The measurement time depends strongly on the scattering cross-section of the sample. The wavelength ranges for the TOF systems are also controlled by the scattering cross-section. The available intensity range is determined by the statistical error, which, in turn, depends directly on the measurement time. Another factor is the width of the momentum-transfer range. If

the width of the momentum-transfer range necessary for the experiment exceeds the spectrometer dynamic range, one must carry out additional measurements. For stationary reactors with a fixed wavelength, the dynamic range is determined by the detector sizes. For pulsed neutron sources, the range and dynamic range are tunable for each sample scattering. Indeed, the limit of the YuMO system with respect to weakly scattering samples is, arbitrarily, 0.05–0.1 cm^{-1}. In this case, the momentum-transfer range is about 0.02 $Å^{-1}$ in the Guinier region and up to 0.2 $Å^{-1}$ in the region of large momentum transfers. In this case, the dynamic range is only 10! For strongly scattering samples, the minimally possible momentum transfer reaches 0.006, and the maximally possible momentum is 0.6 $Å^{-1}$ (the dynamic range exceeds 100). Thus, the dynamic range and experiment duration depend strongly on the sample parameters. Note that the time for weakly scattering samples (when one detector appears to cover the entire dynamic range of momentum transfers) can be halved using the second detector (located at the optimal site), because the range of scattering vector **q** will almost coincide with the aforementioned range for each detector due to the use of the TOF technique and possibility of moving the detector.

The Maxwell distribution of the neutron flux incident on the sample causes an exponential decrease in the scattering intensity. This leads to an increase in the exposure time, when one must have sufficient statistics on the wings, i.e., at short (less than 1 Å) and long (more than 4 Å) neutron wavelengths. The use of two detectors eases the requirement to have good statistics for short wavelengths because of the partial overlap of scattering curves. Thus, this factor makes it possible to reduce the measurement time for the overwhelming majority of samples.

It should also be noted that an experimenter often performs test measurements on samples that may have singularities at different points in the momentum-transfer range. These experiments last generally several minutes. In this case, an experimenter does not move the detector, and, therefore, a possible effect may be missed. Thus, the quality of data obtained is much higher when using a wide momentum-transfer range for multidetector data-accumulation system.

5. SOME EXAMPLES OF STUDYING SUPRAMOLECULAR STRUCTURES

Let us consider some examples of studying structures on the YuMO spectrometer, which illustrate the above statements. Intact chicken erythrocyte nuclei were studied in [113, 114] on several small-angle systems in Dubna and Jülich. It was shown that the obtained scattering curve could be interpreted on the scale from 15 nm to 1.5 μm in terms of a mass fractal. The fractal dimension of the protein components of the cell nucleus is a constant approximately equal to 2.5, whereas the DNA has a double-phase organization, and its fractal dimension slightly exceeds 2 for the scale of smaller than 300 nm and approaches 3 on a larger scale. The methodical value of that study was in verification of the coincidence of scattering curves obtained on the upgraded YuMO spectrometer and on the KWS-2 and KWS-3 systems (Jülich Research Center, Germany). The obtained straight lines on the double logarithmic scale coincide in the region of overlapping momentum-transfer ranges and determine the left boundary for the measurements performed on the YuMO spectrometer.

The fractal organization of colloidal soil components was considered in [115–118]. The curves from those samples were measured in the dynamic range of 90 (range of scattering vectors from 0.007 to 0.6 $Å^{-1}$). More than 20 types of soils and horizons were considered. It was shown that the fractal dimension depends on the soil type and horizon, degree of saturation with water, and temperature. Some conclusions on the fractal structure were made due to the wide dynamic range. The wide dynamic range (up to 200) and possibility for carrying out measurements at small (less than 10^{-2} cm^{-1}) and large (up to several hundred cm^{-1}) differential scattering cross-sections made it possible to study polymer membranes on the YuMO spectrometer [119]. The complementary approach implied the use of the spin-echo method.

The kinetics of the mechanism of bacteriorhodopsin crystallization in the cubic lipid phase was studied in [120].

The onset of crystallization process with salt added decreases significantly the lattice parameters. The symmetry type and lattice parameters were determined, and the change in the kinetics of parameters was analyzed. From the methodical point of view, a good resolution of the system was demonstrated. When studying the kinetics, the measurement time per experimental curve was 3 min.

The phenomenon of charge-induced microphase separation in polyelectrolyte hydrogels was investigated in [121]. The aggregation number was determined. It was shown that the size of hydrophobic region decreases with an increase in the charge concentration. The microphase separation disappears when adding salt. The model describing this behavior of polyelectrolyte hydrogels was constructed. A wide dynamic range was used, because polyelectrolyte hydrogels are structurally ordered on different size-scale levels.

The effect of incorporation of antibiotic AmB into membranes of egg phosphatidylcholine in the concentration range from 0.01 to 5 mol % on the structure and dynamic properties of lipid bilayers was studied in [122] using three methods: SANS (YuMO spectrometer), X-ray diffraction (XRD) analysis (DRON-4), and IR spectroscopy (FTIR). The experiments showed that the antibiotic was located mainly near the

leading groups of membranes at concentrations lower than 1 mol %, and that AmB is incorporated into the hydrophobic membrane part at higher concentrations.

The pyrolyzed derivatives of bis-yttrium phthalocyanine were studied by AFM, IR spectroscopy, and SANS. It was shown that pyrolysis induced formation of thermostable structures, the packing of which is determined by temperature. Loose chain structures, consisting of small carbon clusters, dominate at low-temperature (less than 1000°C) pyrolysis. The sample surfaces were visualized using AFM [123].

The study of magnetic fluids began in the beginning of the 1990s in [93], where it was shown how to separate the nuclear and magnetic contributions to the scattering intensity using a system free of magnetic field and polarized neutrons, and continued on the upgraded YuMO system [94]. It was shown in [93, 94] that one can separate the contributions from nuclear and magnetic components by varying contrast in the SANS experiment with unpolarized neutrons. As was noted, it was an absolutely novel result for that time.

There is a tendency in structural studies of biological objects to pass from analysis of individual proteins, membranes, and even complexes to the analysis of these objects in the composition of organelles. For example, the structures of membranes of intact mitochondria were studied on the upgraded YuMO spectrometer in [31–33, 35]. The small-angle experiments showed that ultrastructural transformations occur in the mitochondria of rat liver and heart when swithcing-on the volume-regulation system. Occurrence of diffraction peaks was observed, which indicated formation of ordered structures in organelles. Based on the positions of these peaks, it was revealed that the packing of cristae changes from disordered to ordered double-membrane packing with a distance of 190 Å between the membrane centers when liver mitochondria are under hypotonic conditions. Under the same conditions, the packing of cristae in cardiac mitochondria changes from a lamellar packing with a distance of 220 Å between membrane centers to, presumably, a hexagonal packing with a lattice parameter of 250 Å. The beam spectrum on the YuMO spectrometer is known to contain both fast neutrons and gamma-rays [87]. To decrease the destructive effect of this radiation on the object, one must shorten the experiment time, using to this end a two-detector system for recording scattered neutrons. The breathing control of mitochondria was performed after measurements, which showed their stability to radiation within 0.76 Sv with respect to the gamma-ray flux and 49.9 Sv with respect to the flux of fast and thermal neutrons. Thus, it was shown that the structure of living mitochondria can be studied by the SANS method.

A system for subjecting samples to high hydrostatic pressure was designed and installed on the spectrometer, which made it possible to study phase transitions in the micellar tetradecyl trimethylammonium bromide/heavy water ($TTAB/D_2O$) solutions in wide ranges of temperature, pressure, and surfactant concentration [124, 125].

The kinetics of the micelle–solid phase transition was studied. The phase diagram of solutions was determined, and the transition rate was shown to depend on temperature, pressure, and surfactant concentration. The two-phase coexistence of micelles and precipitates (solid phase) was found in specific ranges of concentration, pressure, and temperature.

A unique PVT system was recently designed and developed, which makes it possible to carry out structural neutron studies and to measure the change in the volume simultaneously [126]. The dynamic range is a critical parameter when studying lipid membranes. Indeed, in the case of a wide dynamic range, one can simultaneously track both the measurement of the repeat distance of lipid membranes and the lipid-bilayer thickness.

The experiments performed with mixtures of lipid membranes on the upgraded IBR-2 reactor using the PVT system showed for the first time occurrence of a simultaneous jump in the isothermal compressibility and minimum in the derivative of the repeat distance of the DPPC/POPC mixture at excess water.

In the cycle of studies [98, 127–129] devoted to the structure of poly(allyl)carbosilane dendrimers, the specific features of interaction of these nanodispersed objects with a solvent, and their organization in solution, their quantitative characteristics were obtained: sizes for several generations and average scattering density.

The application of modern data processing methods using the good resolution of upgraded small-angle spectrometer YuMO made it possible to characterize the shape of dendrimers of several generations for three- and four-functional nuclei. The penetration of solvent into dendrimer suggests that these new artificial large molecules can be used in practice. Specifically the wide range of momentum transfers (from 0.007 to 0.4 $Å^{-1}$) and the absolute intensity scale allowed to reconstruct the structure of dendrimers and specific features of their interaction with the solvent. The spatial distribution of the scattering density of the dendrimers under study was reconstructed using the modern formalism applied in analysis of experimental SANS data [130]. It was proven by the method of SANS contrast variation that the dendrimer molecules in the solutions do not contain any closed internal large cavities unavailable for solvent. Based on the SANS intensity measured in absolute units, the partial volume of dendrimer in solution was determined, and the volume fraction (30–40%) of open internal cavities in the effective dendrimer volume that are available to the solvent was calculated [131, 132]. The shown anisometry of the shapes of dendrimer macromolecules (which contradicts the AFM data) was confirmed using the molecular dynamics results.

The combination of quasi-elastic scattering, UV spectroscopy, and X-ray scattering makes it possible to determine with high precision the distribution of nanoparticles [133]. The specificity of measurements on the YuMO small-angle neutron spectrometer was discussed in [134]; in particular, the possibility for measuring the sample transmission in two ways without changing the existing measurement procedure, experimental background conditions, and a possible use of another scatterer were considered.

CONCLUSIONS

Small-angle neutron instruments have been in operation for about half a century. One of the first studies on the research potential of the system of small-angle scattering (SANS-YuMO, JINR, Dubna), was published in the journal *Uspekhi Fizicheskikh Nauk* (*Physics-Uspekhi*) in 1982 [135]. The biological potential of the system was never doubted by the authors. Despite the fact that the main trend in structural biology is determined by the progress in protein crystallization and development of synchrotron beams, there are some problems (primarily related to the native state), where the importance of SANS can hardly be overestimated.

At the same time, other lines of research appeared, some of which are discussed in this brief review. They, in turn, determine the instrumental requirements; simultaneously, methodical achievements open new fields in the study of supramolecular structures.

Let us formulate the main requirements to a modern small-angle scattering facility. The first requirement is a high rate of experimental-data accumulation and a wide dynamic **q**-range due to the use of different versions of multidetector systems. The second requirement is a user-friendly interface and remote control of experiment. The third requirement is a possibility for carrying out experiments with many other devices providing wide-range variations in external conditions for a sample: temperature and pressure, illumination, and magnetic and electric fields.

During experiments, as a rule, the values of parameters and all coordinates of spectrometer engines are tracked, with electronic logging. As a result, systematic errors are excluded, and there is a possibility for obtaining information about the spectrometer configuration and state of parameters on the sample. Simultaneously, scattering curves are calculated automatically in a relatively narrow range of scattering vector magnitudes.

Despite the fact that the intensity curve in absolute units is required rarely (immediately after the experiment and during it), this characteristic may also be an actual requirement. This feature makes an undoubted advantage and yields additional information when studying molecular and supramolecular structures in comparison with the scheme conventionally used on other instruments (additional measurements of water, carbon, or some other references are performed after (before) the experiment).

A resolution is also a key parameter of a small-angle system. In this case, the resolution is the sum of the TOF component (which is very good due to the pulsed mode of reactor operation), collimation component (the collimation-base length), and the detector spatial resolution.

Therefore, further development of SANS technique on the fourth channel is primarily related to the method for detecting thermal neutrons. Almost all small-angle scattering instruments are equipped with two-dimensional position-sensitive detectors (PSDs). Concerning the spectrometer YuMO in Dubna, development of a modern two-dimensional PSD was started in the March of 2002. The detector was manufactured and necessary tests were performed at the Leon Brillouin Laboratory (France). Than the detector operated for half a year in the YuMO system in the standard mode in the far position of two-detector system and thus demonstrated its operating capacity [136, 137]. The PSD was designed with a high spatial resolution, which make it possible to start works aimed at using the serious advantage of pulsed reactor in comparison with the stationary one: good resolution with respect to the momentum transfer. The PSD provides additional information about the structure and, therefore, properties of samples and processes occurring in them under exposure to temperature, pressure, light, and humidity.

The question with cold moderator remains difficult to solve. As was noted previously, a significant deterioration in the signal/background ratio may lead to shutdown of a series of lines of research (low-concentration and small-volume liquid biological samples, low-contrast samples, etc.). Thus, the advantage of this tool as a fast-acting system also disappears. To date, the minimum component of the measurement time range on the YuMO spectrometer reaches three minutes per one sample ($I(q)$ curve).

Obviously, the development of new models and processing programs remains a promising trend: not only an increase in the amount of data but also machine learning can be useful when processing of big data.

Undoubtedly, the use of polarized neutrons is a promising direction of development of small-angle systems.

It is also clear that the SANS method is complementary to not only small-angle X-ray scattering but also to the diffraction and inelastic methods of scattering, microscopy, NMR, and densitometry. Specifically the complementarity of methods becomes the main trend in structural research.

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