Progress in SANS Studies of Polymer Systems

(Panel Discussion)

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Availability of Reactor-Based SANS Instrumentation

The aim of the Panel Discussion was to discuss cutting edge research in progress, in addition to predictions and prospects for future developments in the field. However, the first requirement of current and future research is to have access to small-angle neutron scattering (SANS) facilities, many of which are currently located on 20-40 year old reactors, and may become unavailable in the next 1-2 decades. Table 1 lists some of the main facilities that have been used for SANS research. The first instrument (1,2) suitable for the study of polymers was built in the late 1960s at the FRJ2 reactor at the Kernforschungsanlage (Forschungszentrum), Jülich, Germany, and pioneered the use of long-wavelength neutrons and large overall instrument length (~ 40 m). This was a direct consequence of the low source brilliance of neutron sources, which are orders of magnitude below that of x-ray sources. In order to compensate for this difference, it is necessary to use large sample areas (1 - 20 cm^2), which means that the overall size of the instrument must be large in order to maintain resolution in the range 10-2000 Å.

Table 1. SANS facilities, past, present and future.

SANS FACILITIES PAST, PRESENT AND FUTURE

1972-80	FRJ2-JULICH	ILL-D11	
	HARWELL*	ORR-10M*	SACLAY–EL3*
1980-99	HFIR-30M*	BNL*	RISO*
	NIST-8M, 30M	ORPHEE-LLB	ILL-D17, D22
	IPNS-SAD, SAND+	LANSCE+	ISIS-RAL+
	KEK-TSUKUBA+	PSI-VILLIGEN+	GKSS ECN*
	FRJ2-KWS1, 2	JAERI-JRR3	BENSC-HMI
2000-10	FRM	SNS+	KOREA-HANARO
(FUNDED)	TRR11-TAIWAN	ANSTO	ORNL-SANS1, 2
2000-10	ESS+ CNF	AUSTRON+	KEK-JAERI+ ISIS-2+
(PROPOSED)			

*facility no longer in operation
+pulsed source (all others reactor-based)

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The FRJ2 SANS facility (1,2) was the first to employ a large overall instrument size and to boost the flux of the long-wavelength ($\lambda > 4$ Å) component of the Maxwellian spectrum by moderating the neutrons to a lower temperature by means of a cold source containing a small volume of liquid hydrogen at $T \sim 20$ K. This gives flux gains of over an order of magnitude at $\lambda \sim 10$ Å, and it was on this instrument that the first SANS experiments on polymers were performed. The D11 facility, built during the early 1970s on the high-flux reactor (HFR) at the Institut Laue-Langevin (ILL), Grenoble, France, incorporated many of the features of the FRJ2 instrument, including a cold source and long (~ 80 m) dimensions (3). Both the FRJ2 and HFR instrumentation made use of neutron guide tubes as proposed by Maier-Leibnitz and Springer (4) and have both been subsequently upgraded and expanded to be among the most productive SANS facilities worldwide.

Subsequently, over twenty other SANS facilities have been constructed worldwide, though several of these instruments are no longer operational, as indicated in Table 1. This trend can be expected to continue as many currently available facilities were constructed on reactors that were built in the 1960s and 1970s. A recent forward survey (5) estimated that over the next two decades, the installed capacity of neutron beams for research could decrease to a level below one third of the present capacity. Fortunately, the decline in the availability of reactor-based SANS instruments, as exemplified by the recent shutdown of the Brookhaven and Risø National Laboratory reactors, has been offset by two competing trends. Firstly, several new reactors are under construction worldwide (Table 1), along with upgrades to existing sources (e.g., at the ILL in the mid-90s, and ORNL during 2000-2003).

SANS Instrumentation on Pulsed Sources

In addition, a range of accelerator-based SANS instruments have been developed over the past 15 years, and, in particular, a spallation neutron source is under construction at Oak Ridge (6). In Europe, the planned European spallation source (7) and/or a second target station at ISIS (8) would do much to offset and even reverse predicted decline in the availability of SANS facilities. Thus, it seems likely that pulsed sources will make a much greater contribution to SANS studies of polymers in future than they have in the past. Also, reactors have been optimized over the past several decades, and the flux of instruments planned on new or upgraded reactor sources will either be less than or equal to the current state of the art instruments (e.g. at D22 at the ILL). However, this is not the case for pulsed facilities, which have not yet begun to reach their full potential so we can still expect order-of-magnitude gains over the current facilities, via the ESS,

SNS, ISIS-2, etc. Some of the opportunities created by this development were described by S. King during the Discussion and are explored in more detail in the Appendix.

Inelastic Effects in SANS

Since the 1970s, the treatment of SANS data has been based on the assumption that the scattering is predominantly elastic and the data may be integrated over all energies to give the time-averaged structure of the system. However, few studies have been performed to check whether inelastic effects may be safely neglected, as currently assumed, and those that have been undertaken indicate that this may not always be the case. For example, critical scattering from binary mixtures of metallic alloys near the phase demixing temperature (9), with an incident wavelength of $\lambda_0 \sim 5$ Å, showed a strong inelastic component at Q values that are typical of many SANS studies (0.01 - 0.4 $Å^{-1}$), as shown in Fig. 1. At higher Q values, which are still within the range of current (e.g. D22 at the ILL) and planned (10) facilities, the elastic peak *virtually disappears from the spectrum* (Fig. 2).

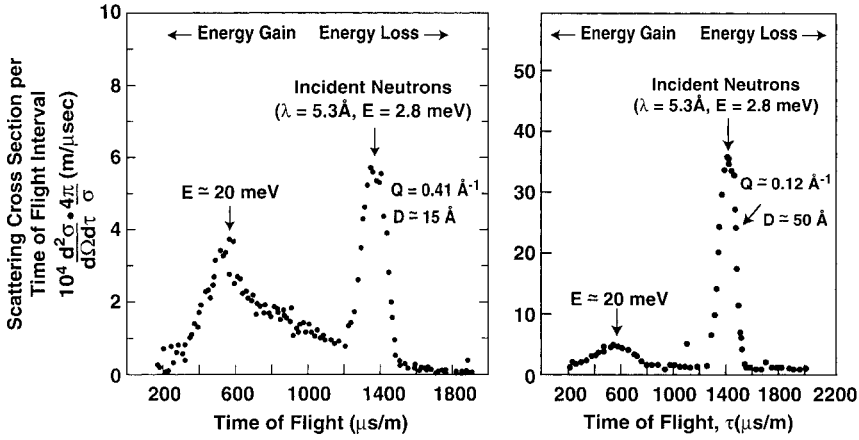

Figure 1: Inelastic spectrum from Bi-Zn solutions (646 °C) near the phase boundary for demixing [*J. Phys. C*, 1, 1088 (1968)].

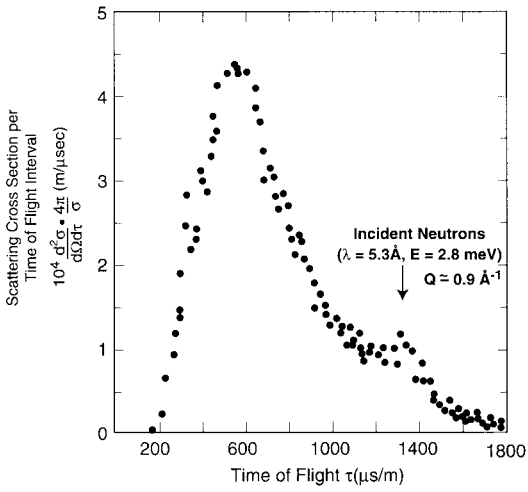

Figure 2: Inelastic spectrum from Bi-Zn solutions (646 °C) at higher Q ($Q_{elastic} \sim 0.9$ Å^{-1}).

For "soft matter" such as polymers and longer incident wavelengths, inelastic effects can be large even at low Q values, as shown by the analysis of the energy spectrum of a beam of 12 Å neutrons, scattered from a variety of solvents and polymer solutions (11). The data indicate that less than half of the neutrons were scattered elastically as assumed by conventional SANS methodology. Strong inelastic effects have also been observed (12) on pulsed facilities (Fig. 3), where they are particularly important as the assignment of the correct Q values is based on the time of flight, which is strongly affected by changes in the neutron velocity on scattering. New detectors such as those being installed on the ORNL SANS facilities (10) will permit time-stamping and these instruments, along with the other new facilities that are planned (e.g. FRM, ISIS-2, SNS, ESS), should have sufficient flux to add an energy analysis capability to the scattered beam. This will permit the option of restricting the measured data to only those events which correspond strictly to elastic scattering, and allow systematic studies of inelastic effects in SANS to delineate more precisely the types of experiments where the "standard" methodology is appropriate.

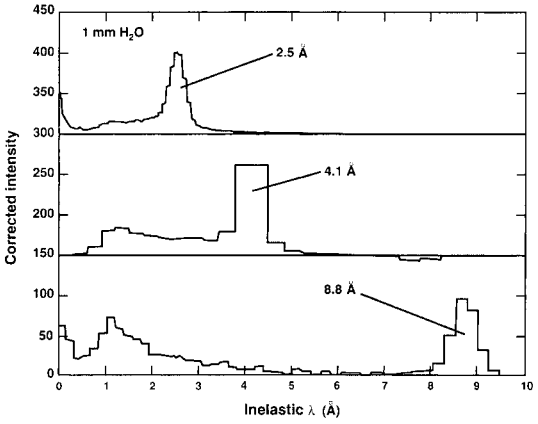

Figure 3: Inelastic spectrum for H_2O recorded on ISIS-SANS with different incident wavelengths [*J. Appl. Crystallogr.* 30, 2240 (1997)].

Time-Resolved Experiments

New high-flux sources will also provide the polymer community with an opportunity to design novel classes of non-equilibrium time-resolved studies and shear-induced phenomena. Processing is a key issue in enabling new materials and technology to reach the market place, and also an area that lags behind synthesis and morphology. Deformation leads to changes in morphology that must be studied under actual conditions, and flow instabilities in polymer extrusion are often the most vexing problem in the commercialization of new products. The need for analyzing systems close to actual processing conditions has been recognized previously (13), and neutrons have a unique advantage since they can penetrate macroscopic extruders and flow devices. Thus, SANS is the technique of choice for exploring the effects of flow in industrially relevant equipment.

Overlapping SANS and Light Scattering

Other instrumental developments have shown promise of lifting the upper resolution limit for pinhole SANS and SAXS instruments, which has traditionally been ~ 10^3 Å. Improvements in the field of ultrasmall-angle neutron scattering (USANS) should make it possible to routinely decrease Q_{min} by an order of magnitude, thus permitting overlap with light scattering techniques. In the mid-1960s, Bonse and Hart (14) pioneered the use of ultrahigh resolution small-angle x-ray scattering (USAXS) techniques, which used double perfect single crystals to Bragg-reflect the beam with an extremely small angular divergence. By using channel-cut crystals, the wings of the rocking curve (which determine the ultimate resolution) can be dramatically reduced. The

critical parameter characterizing the sensitivity is the width of the rocking curve of the analyzer crystal (i.e., the intensity suppression at an angle of ~10", relative to the zero-angle intensity) and the best value of this parameter for USAXS diffractometers is ~ 10^{-5} at $\lambda \sim 1$ Å.

Attempts to apply the double-crystal technique for neutron diffraction have been less successful, as the rocking curve parameters (~ 5 x 10^{-3}) have been much higher than for USAXS diffractometers. It was eventually discovered (15) that the wings of the rocking curve had been contaminated by a parasitic neutron flux, propagating inside the single crystal. Channel-cut crystals that have been modified to include neutron absorbing components (Cd) to prevent the propagation of neutrons inside the crystal, have been shown to give rocking curve parameters similar to USAXS, and thus dramatically improve the sensitivity (Fig. 4). In addition, etching the crystals to remove surface imperfections further enhances the sensitivity by another order of magnitude (Fig. 4).

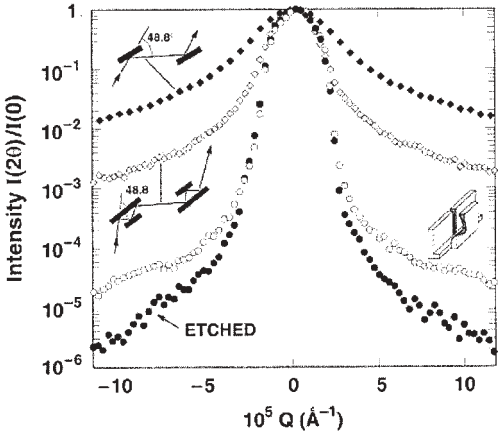

Figure 4: Rocking curves for single- and double-bounce crystals. A Cd-absorber prevents propagation inside the Si walls and improves the USANS sensitivity. Etching removes surface imperfections and further enhances the sensitivity.

These improvements in the signal-to-noise allow the study of particles with dimensions up to 10-30 μm, thus overlapping with light scattering techniques, and an upgraded USANS instrument has recently been installed at the ILL, containing an "Agamalian cut" in the multiple-bounce crystals (16).

However, Bonse-Hart instruments do not measure a two-dimensional pattern and the data are slit-smeared. Alefeld and co-workers (17,18) have proposed an alternative design using focusing toroidal mirrors (FTM) and a demonstration instrument will shortly be commissioned at the FRJ2 reactor in Jülich (19). The advantages of this design are that the FTM-SANS instrument is quite compact and so count rates remain high. Furthermore it also measures a 2D scattering

pattern. Provided the technological problems of mirror fabrication and the need for a high-count-rate detector with millimeter resolution can be overcome, this type of instrument would be an excellent choice for a pulsed source and would open up a whole new area of science at the neutron/light scattering interface.

USANS is useful not only in exploring large length scale structures but also in analyzing line profiles of sharp diffraction peaks which appear in a small-angle region. The latter utilizes the sharpness of the rocking curves in USANS apparatus and will yield important information on various elastic moduli for thermally stimulated modes of deformation of the structures associated with the diffractions. USAXS is also useful in the same sense as described above, some application of which have been reported (20) for investigation of order-disorder transition in block copolymers.

Complementary SANS and SAXS Structural Investigations

Professor T. Hashimoto (Kyoto) introduced this subject and gave examples from his research on block copolymers, which are produced by joining two or more chemically distinct polymer blocks, that may be thermodynamically incompatible. Segregation on the molecular scale (10-1000 Å) produces complex nanostructures by self-assembly. The simplest molecular architecture is obtained by connecting a block of A units with a block of B units to make an A-B diblock copolymer, and more complex molecules can be created by linking together three or more monomer unit types.

Two competing effects govern the structure and at high temperatures (T), the chains having UCST-type segmental interactions, for example, are mixed homogeneously. As T is reduced, incompatible blocks tend to segregate due to the different chemical affinities of the components, though the bond between polymer blocks constrains intrachain block separation to a length-scale on the order of the overall chain radius of gyration. In recent years, the rich variety of ordered microdomain morphology of triblock (e.g. ABC) terpolymers has attracted the interest of many researchers (21). So far, most of the copolymers studied have been in the strong segregation regime (where there is little mixing of the A, B and C blocks), and their morphologies have been examined mainly by transmission electron microscopy. However, if one can control the various transitions (e.g. between order and disorder as a function of T) among various ordered phases of multiblock copolymers, it will further enrich potential applications for advanced materials or devices. Scattering techniques are vital for in-situ characterization of the statics and dynamics of such phase transitions as discussed above, and as these systems have

characteristics of multicomponents and multiphases, one has to use contrast variation techniques in order to fully characterize the ordered multiphase morphologies.

An example of such a study (22) was used to illustrate the combined use of SANS and SAXS, coupled with deuterium labeling for exploring phase transitions in a triblock terpolymer, polyisoprene (PI)-*block*-poly(deuterated styrene) (DPS)-*block*-poly(methyl vinyl ether) (PMVE), with number-average molecular weights of the PI, DPS and PMVE blocks of 5,000, 23,500 and 35,000, respectively. The temperature dependence of the SAXS and SANS profiles exhibited intriguing features, as shown in Fig. 5, where the D spacing estimated from the scattering vector Q_m of the first-order maximum is plotted as a function of the inverse temperature (K) for SAXS (open squares) and SANS (filled squares). At $T < 140$ °C, the SAXS and SANS D values have a similar temperature dependence, while at $T > 140$ °C, the temperature variation of D for SAXS and SANS are completely opposite. Moreover, the SAXS profile showed a double maximum and spacing, though the SANS profile did not. Noting that the SANS contrasts of PI and PMVE are about equal but much less than that of DPS, and that the SAXS contrasts of DPS and PMVE are similar but greater than PI, the striking temperature dependence of D can be interpreted as follows.

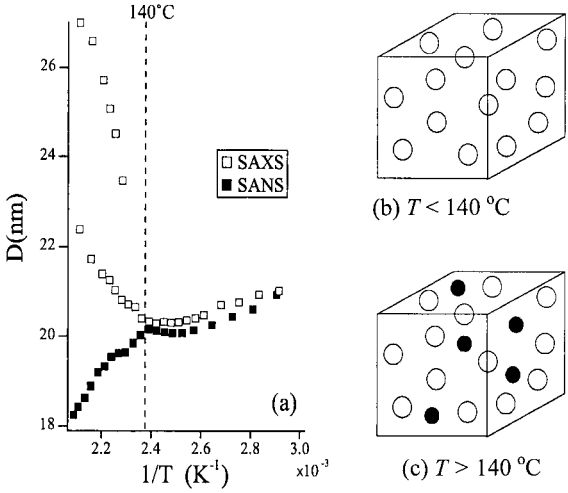

Figure 5: (a) Temperature dependence of the domain spacing D as calculated from the first-order scattering maxima for SAXS (open squares) and SANS (filled squares) from a PI-*b*-DPS-*b*-PMVE triblock terpolymer. Schematic model for the domain structure at (b) $T <$ 140 °C and at (c) $T >$ 140 °C. The spheres shown by open and filled circles represent, respectively, spheres composed of PI and PMVE blocks.

At temperatures lower than 140 °C, the spherical microdomains of PI block are dispersed in the matrix of mixed DPS and PMVE blocks. Conversely, at temperatures higher than 140 °C, the PMVE blocks undergo microphase separation from the matrix of mixed DPS and PMVE, so that the spheres of PI and those of PMVE coexist. A plausible explanation of the striking differences between SAXS and SANS for $T > 140$ °C is that SAXS "sees" only the PI spheres, while the SANS "sees" both the PI and PMVE. Moreover, microphase separation of PMVE spheres would occur as a result of segregation of PMVE blocks from the DPS chains anchored by the PI spheres. This phenomenon may cause fluctuations in the association number of PMVE blocks in PMVE spheres, which, in turn, may cause a large-length-scale heterogeneities in number density of PI spheres (22). Thus, the complementary information provided by SANS and SAXS helps to characterize the structure and transitions in a way that neither technique alone could do, and is a possible argument in favor of locating neutron and x-ray scattering sources on the same site (e.g. Grenoble).

Retrospective on "Neutron Scattering in the Nineties"

In order to assess the utility of forecasts of future developments in the field, as attempted in this article, it may be instructive to review previous attempts to do so. Then as now, the availability of SANS facilities was a concern and it was hoped that there would be an approximate doubling of the number of reactor neutrons incident on samples "over the next decade" (23). This prediction has come closer to realization in Europe, where the commissioning of new instruments at the ILL, Jülich, Hahn-Meitner, and Paul Scherrer Institutes has more than offset the loss of the Risø reactor. However, in the U.S., the cancellation of the Advanced Neutron Source and the Missouri University Research Reactor scattering program, and the permanent and temporary shutdowns of the Brookhaven and LANSCE sources have largely negated the forecast that polymer scientists will be more prone to use the technique with increased beam time availability (24). NIST has remained the main "workhorse" for polymer-SANS research and projections that "increased flux will lead to a proliferation of kinetic and time-resolved studies" will have to await new and upgraded facilities before they are fully realized.

On the other hand, predictions that absolute calibration will become routine, that the gap between SANS and light scattering will be closed, that equipment will be more user-friendly as changes in sample-detector distance and beam collimation will be more easily accomplished, and faster computers will permit real-time analysis and comparison with theory have been largely

authenticated. In addition, the forecast that solid-state detectors will be developed for better Q-resolution and/or more compact equipment has been partially fulfilled, as new area detectors have been constructed for the FRJ2 SANS instruments. Further developments along these lines could be of even greater importance for the future of pulsed SANS facilities.

Finally, it may be worth re-emphasizing a point made at the "Neutron Scattering in the Nineties" Symposium (24) as follows:

"The greatest limitation for SANS experimentalists is the securing of suitable samples. To take full advantage of the power of SANS, samples should be selectively deuterated in designated places. The investments in SANS experiments is great enough that samples should be well characterized for MW, tacticity, etc."

In view of the planned large investments in new sources, upgrades and instrumentation, the commitment of a small fraction of this amount to a complementary synthetic program could dramatically increase the overall impact and productivity of future research on polymers.

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APPENDIX: NEW SOURCES - NEW OPPORTUNITIES

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Historical Perspective

Most neutron scatterers would probably agree that the high-flux reactor at the Institute Laue-Langevin (ILL) in Grenoble represents the best steady-state neutron source in the world today (A1). Commissioned in 1971, but refurbished in the mid-1990s, and with an ongoing program of technical and instrument development, it will no doubt continue to play a significant part in the research careers of many a polymer scientist for at least a couple more decades.

However, as our scientific curiosity develops, so do the demands we place on neutron facilities and their instrumentation. We want to do experiments faster, or with better precision, or with higher resolution, or indeed with any combination of the above. This is of course a trend that is not unique to neutron scattering, but because the facilities involved are large and expensive they must be planned years in advance and designed in such a way that they are utilized to the fullest possible extent. There are currently something like 41 neutron sources around the world operating as "user facilities" (A2). Of these 24 are in Europe (including Russia), 9 are in North America (including Canada), 5 are on the Pacific Rim, 2 are on the Indian sub-continent, and 1 is in North Africa. And there are probably a few others not counted in the above. Of these sources, 36 are reactor facilities, but two-thirds of them were commissioned more than 30 years ago and, consequently, now have increasingly finite lifetimes. New sources are therefore needed. Not just to replace what will be an inevitable decline in measuring capacity, but to ensure that the instrumentation at the disposal of the experimentalist is "state of the art". Building new reactors though is unlikely to be the answer.

To improve on the performance of the ILL reactor (core flux 1.5×10^{15} n cm^{-2} s^{-1}; 58 MW) would be difficult. Difficult technologically (because we are at the limit of our ability to

remove heat from such compact reactor cores even though commercial power reactors are typically 1000 MW), difficult politically (because a "next-generation" ILL would need enriched fuel which is subject to international treaties), and difficult environmentally (because the mood of the public has changed and reactors are no longer seen as desirable). Nevertheless, a handful of new reactors have come online (e.g. HMI, JAERI) or have been refurbished in the last 10-20 years (e.g. FRJ2 in the mid-80s, ILL in the mid-90s; ORNL during 2000-3) and a new facility (FRM-2), comparable to ILL in flux terms, is under construction in Munich, Germany (A3).

Spallation Sources

The alternative to building reactors is to use particle accelerators to produce neutrons. Four spallation (or pulsed) sources have been in operation since the 1980s (ISIS in the United Kingdom (A4), KENS in Japan (A5), and IPNS (A6) and LANSCE (A7) in the United States), whilst a continuous variant came online at the Paul Scherrer Institute (PSI) in Switzerland in 1995 (A8). At the time of writing (mid-2001), the US is constructing a "next-generation" spallation neutron source (simply called the SNS) at the Oak Ridge National Laboratory (A9), whilst members of the European Uni-n are considering a proposal for an even more powerful facility (the European Spallation Source or ESS (A10)).

The spallation process involves bombarding a heavy metal (e.g. Ta, W or even Hg) target with relativistic (high-energy) protons. Protons hitting nuclei trigger an intranuclear cascade, placing those nuclei into a highly excited state. These lose energy by "evaporating" nucleons (mainly neutrons). In the case of a tungsten target, each proton delivered results in the production of approximately 15 neutrons but, importantly, with only modest heat production. In most instances the protons are accelerated in pulses and so neutron production also occurs in pulses. This allows the neutron instruments to employ time-of-flight (TOF) techniques.

Essentially, shorter-wavelength neutrons travel faster, and so arrive at a detector earlier, than longer-wavelength neutrons. There is thus no need to employ a velocity selector to monochromatize the incident beam. Wavelength resolution (and hence Q resolution, where Q is the scattering vector) is then largely determined by the precision with which the neutrons can be timed and is, consequently, very good. For a pulsed-source SANS instrument, a figure of 5 % would not be uncommon, compared to 12-30 % for its reactor counterpart (A11). Allied to this is the fact that the count rate at a detector varies as the inverse fourth power of the Q resolution (A12) and so a pulsed-source SANS instrument will generally outperform a reactor-SANS instrument at intermediate Q values anyway.

The other benefit of the TOF approach is that any given point on a detector corresponds to several different Q values, determined by the wavelength of the neutrons arriving there. Hence the broader the incident wavelength band, the greater the range of Q values that can be measured with any given configuration of the instrument. Pulsed-source SANS instruments therefore have much greater dynamic range in Q than reactor-source instruments. As an example, the SANS instrument at ISIS [called LOQ (A13)] can simultaneously measure the range $0.06 < Q\ (nm^{-1}) < 16$ (though to do so it must operate at half of the source frequency and thus pays a flux penalty). Not having to make measurements (or re-do calibrations) at multiple sample-detector distances and/or at different wavelengths is also a significant experimental advantage of pulsed-source SANS which should not be overlooked lightly. Indeed, polymeric systems often exhibit structure on a range of length scales from phase dimensions to radii-of-gyration to persistence lengths, which require a wide dynamic range.

One important point that should be borne in mind is that none of the operational spallation sources were designed for cold (long-wavelength) neutron production - the source frequency is typically higher than is optimal (e.g. 50 Hz at ISIS) and the cold moderators are decoupled (i.e., separated from the target by a layer of neutron absorber) - so no one has yet truly experienced the best that pulsed-source SANS potentially has to offer. This will change once the new sources come onstream and the existing ones upgrade.

To put these sources in perspective, the most powerful at present is ISIS with a beam power of 0.24 MW (A14). By contrast, the SNS will be a 2-MW source when it comes online in 2006, and the ESS will have a 5-MW target station. For obvious reasons, these beam power levels cannot be directly compared with the thermal power levels of reactors. Comparisons must instead be made on the basis of the neutron fluxes from the moderators (A15,16). On this basis, and comparing the known performance of the (decoupled) ISIS cold moderator to that of the original ILL cold source, the time-averaged flux from a coupled cold moderator on a 4-MW spallation source is fully expected to be about equivalent to that of the ILL second cold source, which supplies the D22 SANS instrument (A17,18). This would represent something like a factor 50 improvement over the present ISIS cold moderator. The proposed low-frequency second target station at ISIS (TS-2) will have a coupled cold moderator and flux gains of at least a factor 10 are projected (A19). If the TS-2 project is approved, then an entirely new SANS instrument will be constructed on it to take advantage of this.

New Opportunities

Despite some initial skepticism at the outset, cold neutron instruments on pulsed sources have more than proved their worth over the years (A20). The next generation of pulsed SANS instruments will offer polymer scientists new experimental opportunities in several areas, some due to improvements in technology, and others due to the complementary nature of the TOF approach, some aspects of which have been discussed above. Present reactor-based instrumentation can certainly be taken as a measure of what the new pulsed-source SANS instruments will be capable of achieving but, beyond that, comparisons and inferences are at best arbitrary because the different instruments utilize their neutrons differently.

Pulsed-source SANS data are always statistically limited at the extremes of the Q range, but the data in between are generally of very good quality (and always of better resolution) compared to a reactor instrument. The experimentalists will therefore benefit most if they adopt a data treatment that takes this into account, such as model-fitting or inversion, rather than persisting with (albeit perhaps more familiar) treatments such as Guinier plots which are by definition restricted to a narrow range of applicability.

To conclude this contribution, it is worth examining the key aspects of future pulsed-source SANS and how these will benefit different areas of polymer science. Arguably the first, and most important aspect is that the experimentalist will have access to instruments with higher neutron fluxes and higher count rates. At a pulsed source with more than one target station, this gain will principally come through utilizing a higher source frequency but in combination with a reduced wavelength band. In other words, there will be a trade-off between flux and Q range. Two categories of measurement will be possible; those that use the higher flux with acceptable statistics to push the time resolution of experiments, and those that use the higher flux to dramatically improve data quality. In the former category, one can envisage time-resolved and kinetic measurements such as in-situ polymerizations, polymer processing, electrochemistry (including the possibility of gating to the neutron pulse), and parametric studies. In the other category are studies of (even more) dilute systems and inelasticity effects. The more routine use of smaller sample volumes or smaller beam sizes (e.g., to a couple of millimetres) will also be possible with the higher fluxes.

Alternatively, by utilizing a low-frequency target in combination with a broad wavelength band, the experimentalists will have a very wide (and simultaneous) Q range at their disposal. This will be important for experiments where the system is responding to a physical or chemical stimulus on many different length scales, or indeed, where it is not at equilibrium.

Examples include polymers under flow, extrusion, or shear, and studies of complex multicomponent systems such as ternary blends and polymer-surfactant complexes. This aspect will also improve the investigation of anisotropic scatterers like liquid crystals. Though, as has already been discussed, improved Q resolution is an inherent property of pulsed-source SANS, further enhancements will further assist studies of interfacial structures, membranes and other ordered systems. And since most proteins interact with biological membranes, there is likely to be a significant increase in the number of experiments looking at membrane interactions in the post-genomic era. In any event, improvements in Q resolution will allow more value to be placed on deuterium contrast variation studies.

Lastly, advances in other areas of scientific equipment design have generally resulted in more compact apparatuses whilst retaining, or even improving, resolution, etc. Without wishing to gaze too deeply into the crystal ball, in the future there will really not be any reason why an experimentalist should not simultaneously measure the UV/Vis or IR signature of a sample, or even its small-angle X-ray scattering, at the same time as the SANS data are recorded. Exploiting the complementarity of different techniques in this way will prove significant in areas such as biopolymers and polymer crystallization, to name but two.

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A14. Beam power (MW) = 10^{-6} x proton current (μA) x proton energy (MeV). ISIS will produce 300 μA of protons at 800 MeV from March 2002.
A15. In the case of a spallation source, flux is roughly linear in beam power.
A16. In any single pulse, ISIS is at least as bright – in terms of neutrons produced - as the ILL, but the time-averaged output would obviously be lower. This subtlety complicates comparisons of the different types of neutron source. However, provided the pulsed source and its instruments are designed in such a way that all the neutrons in every pulse

can be utilized, it is legitimate to compare the peak flux of a pulsed source with the mean flux of a reactor. A more detailed discussion is presented by F. Mezei, *Neutron News* 5(3), 2 (1994).

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