Neutron scattering with spallation sources

Pulsed neutron sources in conjunction with time-of-flight spectrometry offer both a broader bandwidth of neutron energy and more neutrons with epithermal energy than are possible with reactor neutron sources.

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The other articles in this issue are concerned with the variety of science that goes on at reactor-based neutron sources. Such sources, based on nuclear fission, have been available since 1942. It has been known since the 1930s that neutrons could be produced through spallation by sending a charged beam of accelerated protons or electrons into a target. However, it has only been in the last few years that the intensity of these spallation sources has been sufficient for the range of sophisticated experiments required to study the properties of condensed matter. Today there are a number of operating spallation neutron sources, and more with higher intensity are planned (see the table). In this article we want to explain the difference between doing experiments at steady-state and at pulsed sources, illustrate what has been done with the modest sources now available, and speculate on some future experimental efforts. We do not have space to describe how a spallation source works: this information is presented in detail in earlier articles.[1]

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There are two fundamental differences between a reactor and a pulsed source:

▶ All experiments at a pulsed source involve time-of-flight techniques. The pulsed source produces neutrons in bursts of 1 to 50 microsec duration (depending on the energy) spaced 20 to 100 millisec apart (depending on the frequency); hence the duty cycle is low but there is very high neutron intensity within each pulse. Time-of-flight techniques enable one to exploit this high intensity.

▶ The spectral characteristics of neutrons from pulsed sources differ from those of reactor neutrons: there is a much larger component of high-energy neutrons (that is, whose energy is above 100 meV) than in the thermal spectrum at reactors. The exploitation of this new energy regime is one of the great opportunities presented by spallation sources.

Figure 1 illustrates these essential differences between experiments at a steady-state source (left panel) and a pulsed source (right panel). We confine the discussions here to diffraction. If the time over which useful information is gathered is equivalent to the full period of the source Δt (the situation suggested by the lower right figure), the peak flux of the pulsed source is the effective parameter to compare with the flux of the steady-state source. Often this is not the case, so one compares the time-averaged flux (center panel). For the pulsed source this is lowered by the duty cycle, but with the time-of-flight method one uses a large interval of the spectrum (shaded area). For the steady-state source the time-averaged flux is high, but only a small wavelength slice (stippled area) is used in the experiment. The *integrals* of the two areas must be compared; the pulsed sources now being designed generally compare favorably on this basis with present-day reactors. Finally, one can see from the central panel that high-energy neutrons (100 to 1000 meV) are especially plentiful at the pulsed sources. We can expect that this feature together with the time structure of the source will be exploited in the design of different kinds of experiments at pulsed sources.

Structural investigations

Structural studies determine the po-

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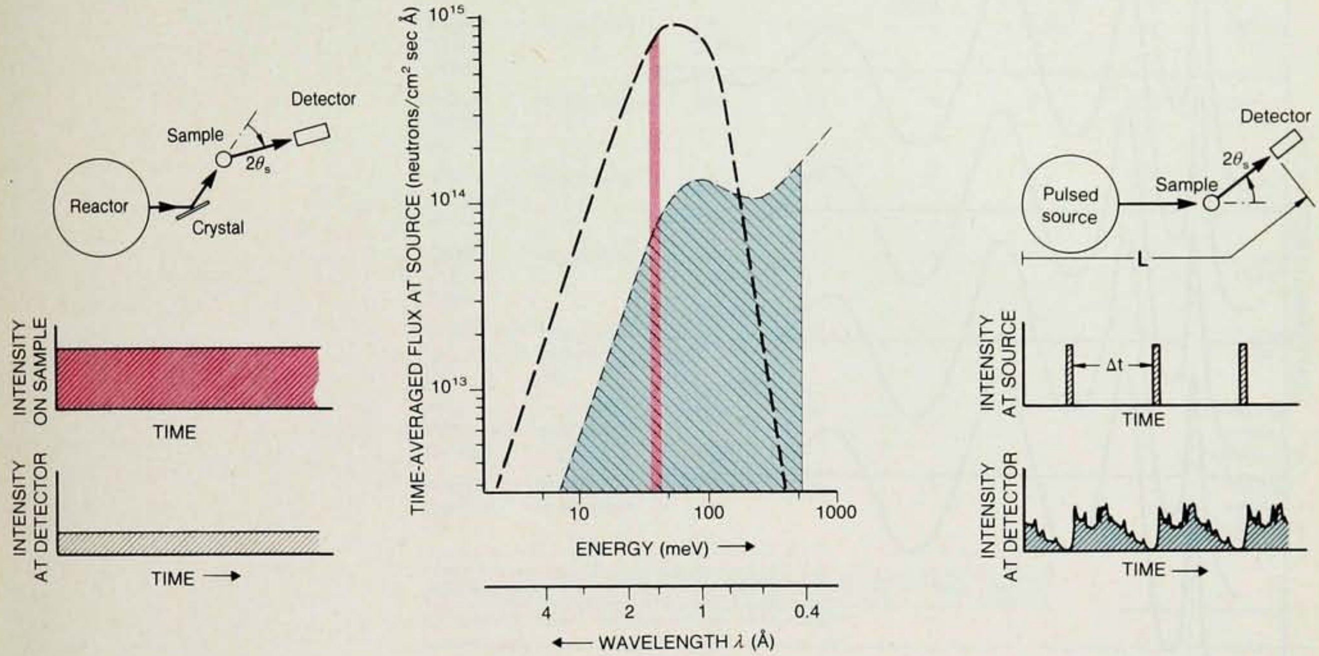
Comparison of diffraction experiments with steady-state and pulsed neutron sources. On the left, the familiar monochromator crystal allows a constant (in time) neutron beam from the reactor to fall on the sample, which then diffracts the beam through an angle $2\theta_s$ into the detector. The signal at the detector is also constant in time. On the right, the pulsed source lets a wide spectrum of neutrons fall on the sample in sharp pulses separated by Δt. The neutrons are then diffracted by the sample through $2\theta_s$ and their time of arrival in the detector analyzed (lower right). The center figure shows the *time-averaged* flux at the source. With a reactor one makes use of a narrow band (shown in red) of the neutron spectrum from the reactor (dashed line), here chosen with $\lambda = 1.5$ Å. At a pulsed source one uses a wide spectral band (blue), here chosen from 0.4 to 3 Å, and each neutron's energy is identified by its time of flight. For the experimenter an important parameter is the integrated area of the two colored areas. Figure 1



sitions of atoms in condensed matter. The angular variations in the scattered radiation from an assemblage of atoms can be related to the actual spatial configuration by the Fourier transform. Thus, by measuring to higher values of the wavevector transfer **Q**, one can get better resolution in real space **R**. For a diffraction experiment (in which a particle of wavelength λ is scattered through 2θ), the value of Q is $(4\pi/\lambda)\sin\theta$. For $\sin\theta$ at its maximum value (at 90°), higher values of Q can be obtained only by decreasing λ. Because spallation sources provide higher-energy (smaller λ) neutrons, they offer the special advantages of improved resolution.

We first consider scattering from amorphous systems, such as a disordered solid or liquid. Figure 2 shows data[2] taken by Masakatsu Misawa and Noboru Watanabe at the KENS facility in Tsukuba, Japan. These data are representative of the current state of the art in glass diffraction. Because the glass under investigation (in this instance, semiconducting $P_{40}Se_{60}$) has no long-range order, there are no Bragg peaks and the structure factor $S(Q)$ is a continuous function. Nevertheless, rather sharp peaks show up for Q near 1 Å^{-1}, indicating well-defined intermediate-range order in the liquid phase; as the temperature is decreased, the peaks move to lower values of Q, suggesting (on the basis of a simple Fourier picture) an increase in the range of the intermediate order. The reasons for this behavior, which has been observed in other semiconducting glasses, are not fully understood. A Fourier transform of the data, which actually extend out to 30 Å^{-1} (not shown in the figure), gives high-resolution information about the local order in real space.

For crystalline materials, the experiment is aimed at measuring the positions and intensities of the Bragg diffraction peaks, using the de Broglie relationship, for neutrons

$$\lambda = h/mv = (0.3955 \text{ Å cm}/\mu\text{sec})t/L$$

where t is the flight time and L is the total flight path. Bragg's law is

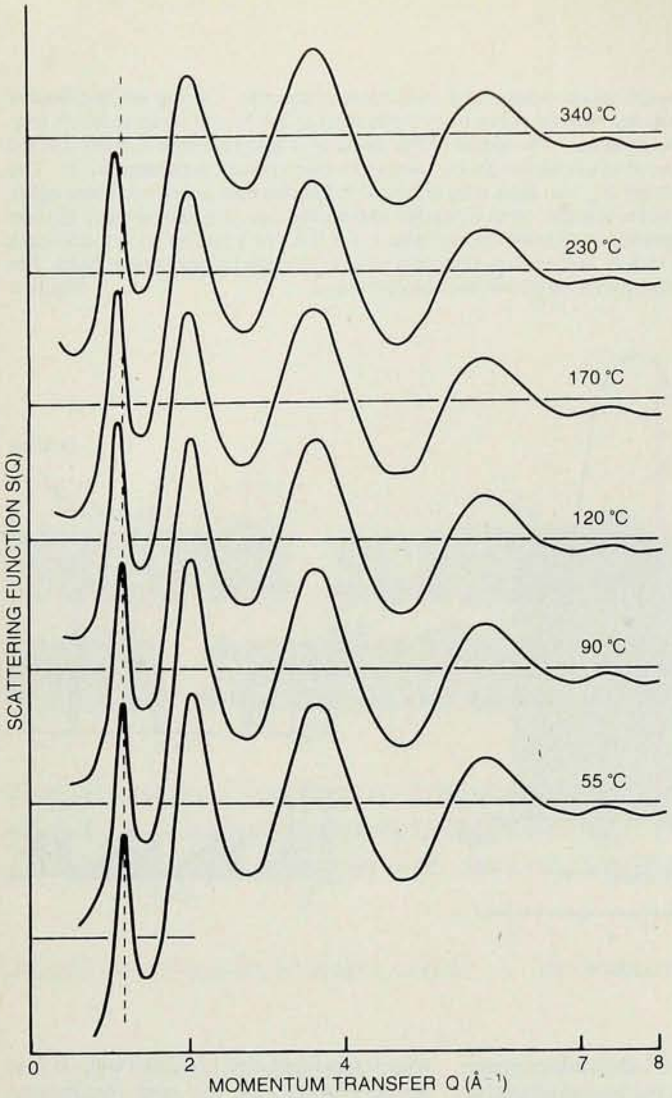
$$2d_{hkl}\sin\theta = \lambda$$

where d_{hkl} is the plane spacing, so that

$$d_{hkl} = \frac{0.3955}{2\times L}\frac{t}{\sin\theta}$$

Experiments at a pulsed source use the "energy dispersive" technique, in which θ is fixed and t is observed. If L is 20 m, θ is 80° (for the best resolution) and d_{hkl} is 1 Å, then $t = 10^4$ μsec. Given that the pulse width at 1 Å is about 10 μsec and that timing can be done to about 1 μsec, the time-of-flight technique is able to provide excellent resolution. The pulsed sources are therefore capable of serving both high-resolution and high-Q studies.

An example has been the work[3] of James Jorgensen and David Hinks on defects in ternary compounds such as $SnMo_6S_8$. These studies have shown that defect oxygen replaces a sulfur atom in the framework and pulls the Sn or Pb atom off its normal site to form a covalent bond. The formation of this defect reduces the superconducting order temperature. Because it is difficult to make oxygen-free Chevrel phases, Jorgensen and Hinks have suggested that the different values of T_c reported for the same compounds are a consequence of oxygen defects, and that there is then a relationship between depression of T_c and oxygen impurity level. The method of data analysis in which all of the pattern is used (called the Rietveld analysis after the Dutch crystallographer who invented it), together with the high-Q



Temperature dependence of the observed[2] scattering function $S(Q)$ for glassy and liquid P_2Se_3. Figure 2

data and good overall resolution, serves as an extremely powerful tool for investigating polycrystalline samples. Because the time-of-flight energy-dispersive method requires only one exit port (fixed θ), it is particularly well adapted for high-pressure studies. Another interesting application of the high resolution has been in metallurgy to determine residual stresses in large samples.[4]

The method for structural investigations of single crystals is conceptually simple. A white (polyenergetic) beam of neutrons impinges on the single crystal in a certain orientation and the various wavelengths are diffracted from the atomic planes according to Bragg's law—the Laue technique. The diffracted neutrons are detected by a position-sensitive detector (of dimensions perhaps 30×30 cm^2) and each event is time analyzed to determine the neutron wavelength. What is unusual and useful about this technique is that it gives a representation of the scattering not only from the Bragg peaks, but also of any additional scattering between these peaks. In figure 3 we see a plot of the intensity distribution in the $(1kl)$ plane from a small (3.4 mg) single crystal of $(TMTSF)_2ClO_4$ at 15 K. The data show that a crystallographic distortion takes place at about 24 K. From a consideration of the intensities of both the superlattice and fundamental reflections (integer h, k, l) the exact atomic shift below 24 K can be determined. In fact the phase transition results in the creation of two crystallographically distinct types of TMTSF columns, each of which may contribute differently to the overall electron transport properties of the crystal.[5]

The last example of structural studies we shall discuss involves neutron *reflection*, rather than diffraction, at a pulsed source. Here the neutron is considered as a wave, with reflection and transmission coefficients at the surfaces of a refractive medium. What is remarkable is that the neutrons are birefringent at a magnetic surface; the interaction of the neutron spin with a magnetic field gives rise to a refraction index of the form:

$$n^{\pm}(z) = 1 - [c_1(b/v) \pm c_2B(z)]$$

where the signs indicate the direction of the neutron spins relative to the magnetic induction B in the material, at the distance z from the interface with the vacuum. The ratio b/v is the nuclear scattering amplitude normalized for the atomic volume, and c_1 and c_2 are parameters proportional to the square of the neutron wavelength. Altogether, the refractive index is different from unity only by a factor of 10^{-5}; hence the neutron reflectivity is normally negligible except when the beam is at grazing incidence with the surface.

The experimental method, which has been set up at Argonne by Gian Felcher and his colleagues,[6] involves reflecting a highly collimated, broad-spectrum beam of polarized neutrons from polished surfaces. By probing a surface of superconducting niobium, the Argonne group has for the first time determined directly the penetration depth of an external magnetic field. The research has gone on to study the superconductivity at the surfaces of lead-based alloys. This relatively simple neutron instrument is quite useful in attacking a variety of problems in which the

Neutron spallation sources*

Facility	Accelerator	Incident proton energy (MeV)	Time average current (μA)	Average pulsing frequency (Hz)	Source pulse width (μsec)	Target material	Status
ZING-P' Argonne, US	Synchrotron	500	3	30	0.1	U^{238}	Operated 1977–80
WNR Los Alamos, US	Linac	800	3.5	120	4.0	W	Started 1977
KENS-I KEK, Japan	Synchrotron	500	2	15	0.07	W	Started 1980
IPNS-I Argonne, US	Synchrotron	500	12	30	0.1	U^{238}	Started 1981
SNS Rutherford, UK	Synchrotron	800	200	50	0.2	U^{238}	To start 1985
KENS-I' KEK, Japan	Synchrotron	500	10	15	0.5	U^{238}	To start 1985
WNR-PSR Los Alamos US	Linac plus storage ring	800	100	12	0.27	U^{238}	To start 1986
SNQ KFA Jülich, Germany	Linac and compressor ring	1100	4000		100	Pb	Proposal under development
ASPUN Argonne, US	FFAG synchrotron	1600	4000	60	0.4		Proposal under development

*Present (and proposed) neutron spallation sources driven by protons in the world. The first such source operated at Argonne in 1974–75 with 0.1 μA current and an energy of 200 MeV. We do not include electron-driven sources here, the largest of which, HELIOS at Harwell, UK, also performs a good deal of condensed-matter research.

magnetic profile close to the surface is desired. Thus, in collaboration with scientists of the IBM research laboratories in San Jose, the group is investigating magnetic tapes prepared with different techniques. The investigators are assembling a more elaborate setup, consisting of an ultra-high-vacuum environment in which metallic ferromagnets can be prepared and studied at temperatures close to the magnetic ordering temperatures, to examine the critical exponents of surface magnetism.

Dynamical investigations

We concentrate here on some of the unique science one can do with epithermal neutrons. Most of these studies involve investigations of the spectrum of energies that the neutron can lose in a material.

To measure the change in energy of the neutron as it traverses the sample, we must define the neutron energy both before and after the sample. Because at a pulsed source each neutron's energy is defined by its time of flight, we may select a monochromatic slice of neutrons, allow them to impinge on the sample and then use the time of flight to specify the final energy. This arrangement is called direct geometry. To define the incident energy we could use a crystal monochromator, but for the higher-energy neutrons a mechanical chopper is probably the best choice because the efficiency of crystal monochromators rapidly drops with decreasing wavelength. Of course, the timing of this chopper must be accurately phased with respect to the pulses from the source (a non-trivial problem!) to select neutrons of the proper speed. Changing this phase relationship selects neutrons of a different incident energy.

An alternative method is to define a final energy (usually by using reflection from crystal planes or a filter with a narrow window of transmission); one can derive the incident energy from a measurement of the total time of flight and thus obtain the energy transfer for a given neutron event. This type of spectrometer has good resolution at energy transfers between 10 and 1000 meV. It is thus ideally suited to measuring relatively dispersionless inelastic modes, such as those that occur with hydrogen in a vast variety of chemical, biological and metallurgical systems; it is to measurements on these systems that the majority of such spectrometers are devoted. Furthermore, the large scattering cross section of hydrogen makes the neutron spectrum rich in proton modes, many of which may be impossible to observe with optical methods.

The application of neutron scattering to vibrational spectroscopy is frequently limited by the relatively low neutron fluxes—as compared with particle fluxes from lasers or electron beams. For example, new materials are often not available in sufficient quantities, and surface vibrational spectroscopy can at present only be applied to molecules adsorbed on powders with a high surface area. Much importance must, therefore, be placed on developing instruments that maximize count rates even at the expense of energy resolution.

The Filter Difference Spectrometer at the Los Alamos pulsed neutron

Intensity distribution on the $(1,k,l)$ plane of $(TMTSF)_2ClO_4$ at 15 K. The superlattice reflections $(1,\frac{9}{2},3)$, $(1,\frac{9}{2},4)$ and $(1,\frac{7}{2},4)$ are clearly observed.[5] Figure 3

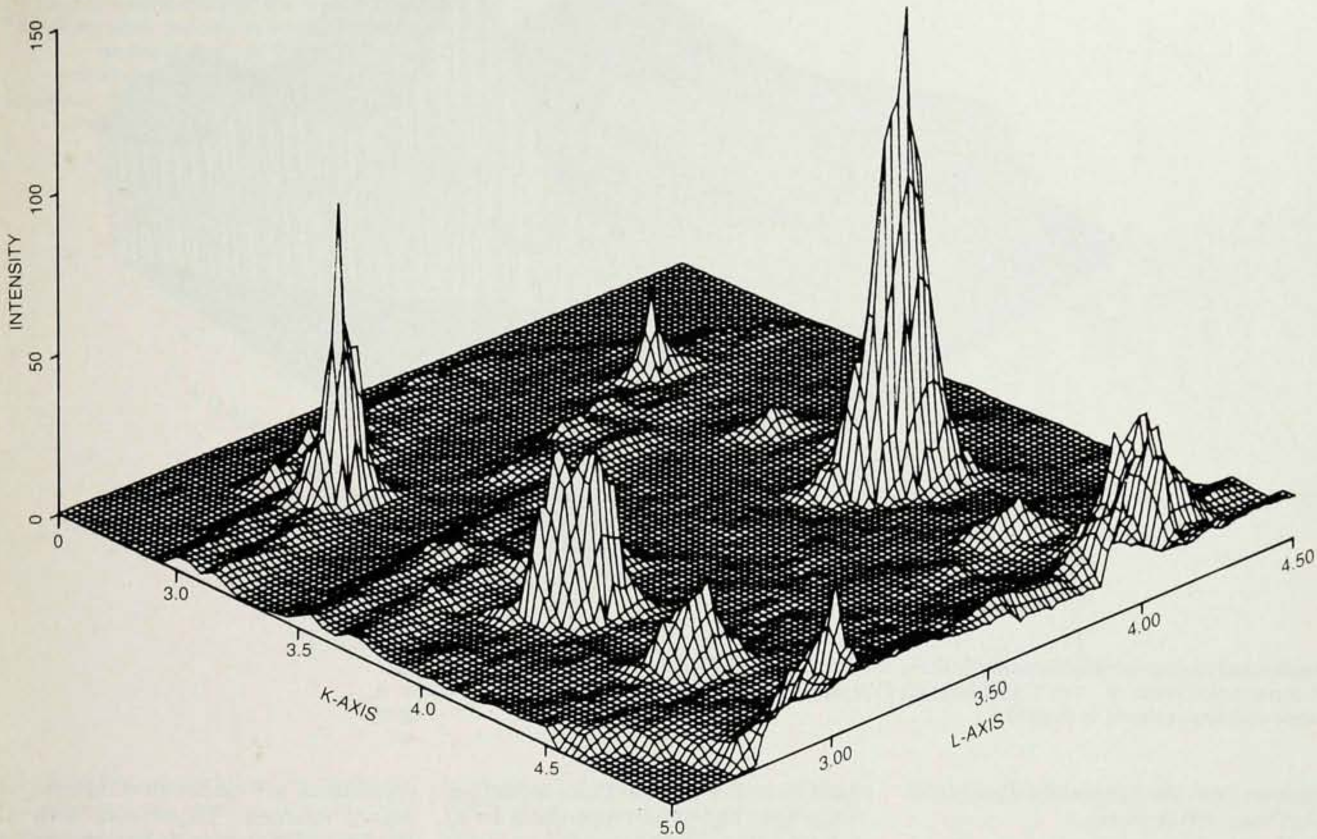
source was designed with these considerations in mind. At present the FDS can measure frequencies from 300 to more than 5000 cm^{-1} (37 to 620 meV) with modest resolution of 5 to 7% ($\Delta E/E$) for most of this range. With the FDS, one obtains a difference[7] between spectra recorded through analyzers made from Be (whose cut off is at 5.2 meV) and BeO (cut off at 3.7 meV) to symmetrize the otherwise asymmetric lineshape of an observed excitation and to limit the band width of final energies to 1.5 meV. The large solid angle and relatively large bandpass for the detected neutrons, as well as a beam size of 2.5×10 cm^2, combine to give the FDS a high count rate despite the relatively low flux at Los Alamos at this time. An upgrade of the facility scheduled for completion in 1986 is expected to increase intensity by a factor of 25 and extend the range of the FDS to much lower frequencies.

Much of the current work on the FDS concerns the vibrational spectra of catalytic systems, such as hydrocarbon adsorbed on platinum black or on zeolites—studies for which high count rates are essential. Neutron vibrational spectroscopy is also well suited for the study of proton vibrations in hydrogen-bonded systems. In a recent work on very short intramolecular O–H–O hydrogen bonds, the frequency of the out-of-plane bend (which had not been assignable using optical techniques) was found to decrease with a decrease of the O–O distance, contrary to the trend that is observed for longer hydrogen bonds.[8] This behavior may be the result of a flattening of the potential well for the proton in these short hydrogen bonds.

In the previous section we discussed modes that are assumed to have frequencies that depend only weakly on wave vector $\mathbf{Q}$. Of course, the power of neutron scattering is that it can measure the dynamical response function over a range of $(\mathbf{Q}, E)$ space, whereas light scattering, for example, is limited to $Q=0$. At pulsed sources we also want to make use of the rich epithermal spectrum to *extend* the coverage of $(\mathbf{Q}, E)$ space available at reactor sources. One particularly challenging portion of this space is the region defined by large E (say, E above 100 meV) and small Q (below 5 $Å^{-1}$).

There are good reasons for this interest. For molecular or liquid systems, if the momentum transfer is large, the excitation is broadened by Doppler broadening due to motion of the particles. In addition, the phonon cross section increases as Q^{2n}, where n is the order of the harmonic, so that higher harmonics rapidly increase in intensity with increasing Q. For electronic excitations (that is, neutrons coupling to the electron spins), on the other hand, the square of the magnetic form factor for all electron shells falls to almost zero by 5 $Å^{-1}$, so that all measurements of such excitations *must* be done with Q below 5 $Å^{-1}$. In performing any scattering experiment we must conserve both energy and momentum transfer, imposing severe restrictions on the experiment. For example, if we want to examine an excitation at 300 meV and a Q near 5 $Å^{-1}$, then the incident energy has to be at least 800 meV and the scattering angle around 10°. This observation requires careful discrimination against both the incident beam and multiple scattering processes (that is, two large-angle scattering events), which are especially strong at small angles.

Figure 4 shows a plot of the scattering function $(E^2/Q^2)S(Q, E)$ in supercooled water (-15 °C) measured on one of the IPNS chopper spectrometers by Sow-Hsin Chen (MIT) and colleagues.[9]



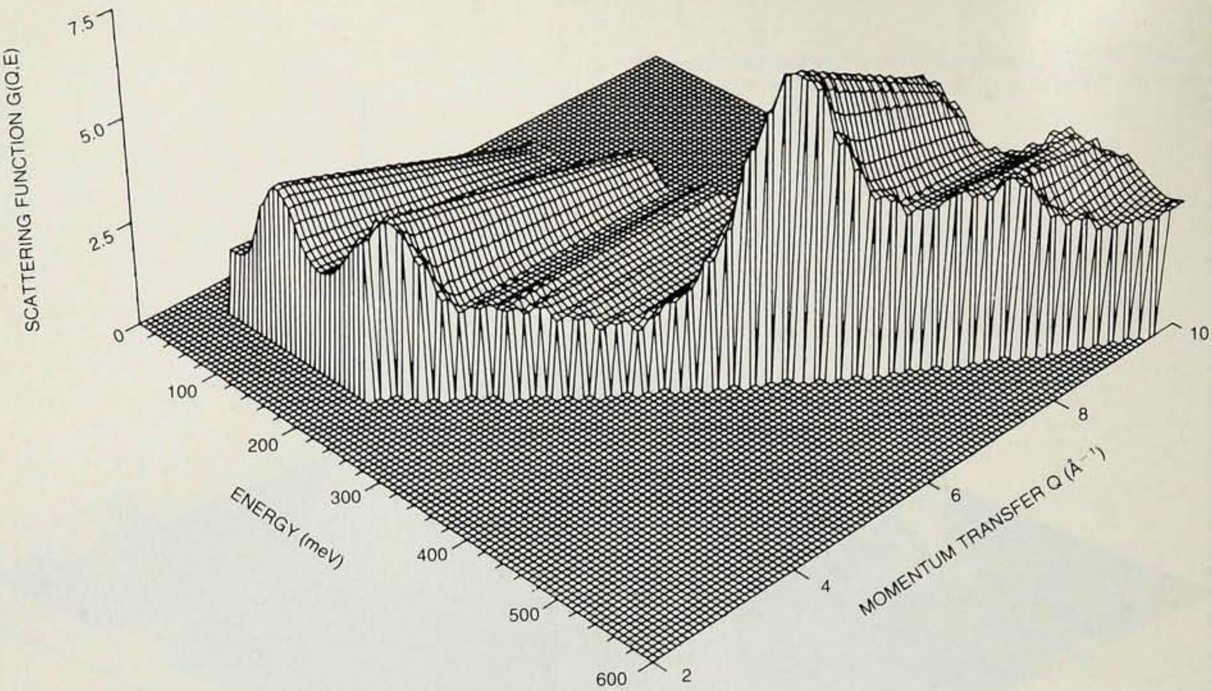
Because neutron scattering from water is dominated by the large scattering cross section of hydrogen, the scattering function represents essentially a wavevector-dependent generalized density of states for the proton motions. Especially pronounced is the large peak at 420 meV due to O–H stretch vibrations. As the temperature of the water is increased, the vibrational frequency also increases—opposite to the usual effect of temperature on vibrational modes. A concurrent study using "molecular dynamics" computer simulations shows that this increase is due to the breaking of the hydrogen bonds, which tend to reduce the frequency of the O–H stretch vibrational modes.

These measurements were made at an incident energy of 800 meV. Even at this high energy, the smallest attainable Q value for the 420-meV mode is about 6 $Å^{-1}$, as seen from figure 4. As Q increases, the vibrational peak broadens and its amplitude decreases. In an earlier measurement at a lower energy of 500 meV, the Q value was about 10 $Å^{-1}$ and the peak, although energetically accessible, was so broad as to be scarcely identifiable.

A different type of study uses the magnetic interaction to measure the spin-wave (collective) excitations in a single crystal of ferromagnetic iron. These experiments have been performed at the IPNS chopper spectrometer by Jeffrey Lynn (University of Maryland), Chun Loong (Argonne) and their colleagues.[10] The magnetic excitations of the elements Fe, Ni and Cr have been of perennial interest because they provide testing grounds for the interplay between localized and itinerant magnetism. In iron, for example, the collective excitations at low energy are well understood, but there is disagreement as to what should happen at higher energy. At some energy the single-particle ("Stoner mode") excitations, which are the signature of the itinerant electrons in the magnets, should appear. So far there is controversy over whether they have been seen at all, and to what extent they will interact with the collective spin waves at similar energies. Experiments at IPNS have already extended the spin-wave spectrum to roughly 160 meV without finding a Stoner mode, and there is great interest in extending this to the vicinity of 300 meV, at which energy a number of theories predict strong interactions between these two types of excitations. It is apparent that these measurements are at the limits of intensity with a modest source such as IPNS, but the rich epithermal spectrum of the pulsed sources and their rapid development clearly gives hope that the definitive experiments are not far off.

Finally, at very large wavevectors we approach the so-called recoil-approximation regime. Here the scattering is centered at the recoil energy $\hbar^2Q^2/2M$ (M is the atomic mass of target atoms), with a distribution about the center that reflects the atomic momentum density $n(\mathbf{p})$ in the ground state. For a classical system this is the well-known Maxwellian function, but for quantum systems such as helium and hydrogen it depends on the many-body wavefunction for the system: $n(\mathbf{p})$ is the Fourier transform of the particle density $|\Psi(\mathbf{r})|^2$. This function is not easy to calculate, even when the interatomic potentials are known, and neutron measurements in the recoil-approximation regime are in fact among the most direct ways to measure it.[11]

A specially interesting case is that of superfluid He^4 where the momentum density can be written in the London formalism as a superposition of contri-



Proton scattering-density function *G(Q,E)*, defined as $S(Q,E)E^2/Q^2$, in supercooled water at −15 °C plotted in (Q,E) space. A fourth peak at 525 meV, probably due to a mode-coupling process, is evident.[9] Figure 4

butions from the normal fluid and from the Bose condensate:

$$n(\mathbf{p}) = (1 - n_0)n^*(\mathbf{p}) + n_0\delta(\mathbf{p})$$

The delta function due to the condensate is reflected as a delta function in the neutron scattering function $S(\mathbf{Q}, E)$, broadened by instrumental resolution and possible effects of final-state interactions. With present instrument resolution and the relatively small values of n_0 (about 10%), it is difficult to resolve this component directly. Instead, one makes measurements at two temperatures above and below the superfluid transition at T_λ, taking care to keep the density fixed. Studies of liquid He^4 as a function of temperature and pressure suggest that $n^*(\mathbf{p})$ of the normal component should be very nearly the same in the two measurements, so a direct subtraction gives

$$n(\mathbf{p})|_{T<T_\lambda} - n(\mathbf{p})|_{T>T_\lambda} = n_0[\delta(\mathbf{p}) - n^*(\mathbf{p})]$$

from which one can obtain the superfluid fraction n_0. Figure 5 shows a corresponding difference plot for the scattering function for liquid He^4 at the saturated vapor pressure, measured by Paul Sokol and his colleagues at the University of Illinois.[12] The lines represent two Gaussian distributions fitted according to the sense of the last equation—a narrow positive component reflecting $n_0\delta(\mathbf{p})$ and a broad negative component, with the same width as in the normal fluid, reflecting $-n_0n^*(\mathbf{p})$. The fit corresponds to an n_0 of 0.10 ± 0.02 at this molar volume. While estimates for n_0 have been determined in the past from data at lower Q, the high-Q technique is especially direct and lends itself readily to detailed studies of the effects of temperature, pressure and the addition of He^3 on the Bose condensate.

Future developments

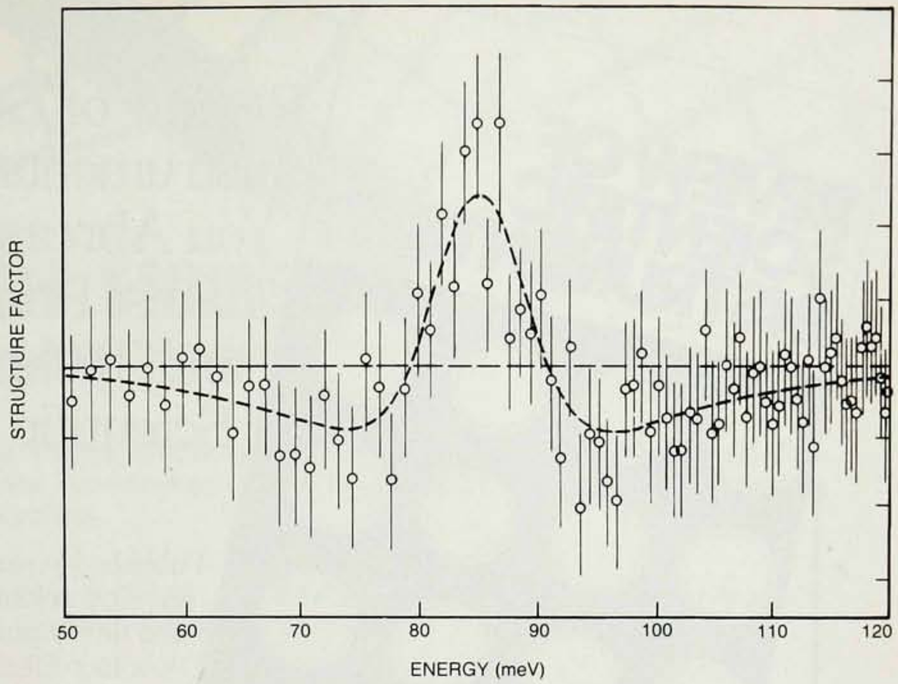
Pulsed neutron sources are relatively new. As with many new scientific technologies, the instrumentation for them is developing at a rapid rate and it is too early to predict the scientific rewards. We mention here briefly four interesting areas:

▶ Spectroscopy in the eV region. Instruments have been set up at a number of laboratories, based on using sharp resonances in materials such as U^{238} (resonance at 6.67 eV). Identification of the final neutron energy is done either indirectly by neutron capture or by detecting the secondary particles emitted (γ rays from U^{238}). Experiments are aimed at either very high-Q recoil scattering (Q around 100 $Å^{-1}$) or electronic excitations at low Q but large energy transfer.

▶ Spectrometers to examine, in single crystals, modes with dispersion. This area of investigation has been a most important one for neutrons (see the articles on pages 27 and 46). Two types of instruments designed to study such excitations are under development at pulsed sources. Experience both at Harwell with the electron linac and at the Japanese source KENS has shown that modes with dispersion can be measured successfully along symmetry directions at a pulsed source. An instrument of this type is also being built at Los Alamos.

▶ Small-angle scattering and the use of cold neutrons. The spectra for the reactor and pulsed source in figure 1 are for room-temperature moderators, but may be shifted down in energy by using cold moderators. Such moderators are in use at both KENS and IPNS, where small-angle and quasielastic scattering are in progress. For small-angle scattering one advantage of the large band width used at a pulsed source (see figure 1) is that a very wide range of Q, perhaps from 0.002 to 0.300 $Å^{-1}$, is available at one setting of the instrument. New experiments designed to capitalize on this dynamic range are being explored at present. At IPNS, Charles Borso and his colleagues have recently performed experiments with chelating agents designed to entrap metal ions, and have shown that the use of resonance effects with Gd^{157} (resonance wavelength of 1.6 Å) greatly increases the sensitivity of the neutron results to the number and form of the Gd atoms entrapped in the micelles. This is a new application of small-angle scattering. It exploits the large bandwidth shown in figure 1 and

Difference plot of the intensity above the lambda point in He^4 subtracted from that below T_λ. The sharp central positive component is due to the Bose condensate whereas the broad negative component is due to the depletion of the normal fluid. Measurements were done with an incident neutron energy of 160 meV and a momentum transfer of 13 $Å^{-1}$. (From reference 12.) Figure 5



has potential application in biology.

▶ Time-resolved studies. Clearly the pulsing nature of the source can be used to advantage if the stimulus to the sample can be phased with the arrival of the neutron burst. Such experiments were performed at the Tohoku electron linac[13] to examine the motion of the domains stimulated by an electric field in the ferroelectric material $NaNO_2$. More recently, again in Japan, relaxation phenomena in spin glasses have been the subject of time-resolved neutron experiments. These results indicate a considerable potential for studies in the time domain of about 1 μsec to 10 msec, and a number of investigations are under active development at pulsed neutron facilities. We should note here that, because a 1-Å neutron travels at a velocity of 4 mm/μsec, studies whose time resolution is less than 1 μsec appear unlikely with present or planned neutron sources and samples.

In conclusion we must once again point out how important the high-intensity sources and improved instrumentation planned for the future are to pulsed-source experimentation. (See reference 14 for a review of instrumentation at pulsed sources.) All sources presently operating, or even under construction, rely on accelerator concepts originated for other scientific applications (high-energy or nuclear physics). Certainly major investments have been made in facilities such as the Rutherford SNS and the Los Alamos WNR/PSR, and when they start operating in 1985 and 1986, respectively, they should move us forward in a number of areas. Nevertheless, accelerator physicists are now beginning to design new types of machines specifically for pulsed-neutron research, and the results, such as the German SNQ or the Argonne ASPUN proposal, are likely to be formidable beasts. They will represent state-of-the-art proton accelerators in terms of proton current, although the energy requirements will be rather modest—below 2 GeV. The production of such proton beams will be useful to a large number of scientists interested in nuclear physics, neutrino production and medical applications in addition to condensed-matter research. The machines will also be very expensive. Building sources of this kind will require the fullest degree of cooperation at the national and, possibly, international level.

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