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Slow Neutron Scattering Experiments

Ralph M. Moon

Summary. Neutron scattering is a versatile technique that has been successfully applied to condensed-matter physics, biology, polymer science, chemistry, and materials science. The United States lost its leadership role in this field to Western Europe about 10 years ago. Recently, a modest investment in the United States in new facilities and a positive attitude on the part of the national laboratories toward outside users have resulted in a dramatic increase in the number of U.S. scientists involved in neutron scattering research. Plans are being made for investments in new and improved facilities that could return the leadership role to the United States.

Neutron scattering has undergone dramatic worldwide growth over the last decade. This growth has occurred in both the number of practitioners and the number of scientific disciplines in which neutron scattering has been productively applied. The trigger responsible for this activity was the success of the Institut Laue-Langevin (ILL) in Grenoble, France. Largely because of ILL, where intense neutron beams, innovative instrumentation, and institutional policies have combined to create a great interest in and demand for neutron scattering facilities, the leadership in this field has shifted from the United States to Western Europe.

This article describes the scientific diversity of neutron scattering, discusses the growth of the U.S. neutron scattering community, and reviews plans for restoring the United States to a position of leadership in this important field. These topics have been the subject of several recent review articles and national discussions about the application of neutron scattering to condensed-matter physics (*1*), biology (*2*), and polymer science (*3*); about ILL and other European activities (*4*); about pulsed neutron sources (*5, 6*); about instrumentation at reactors (*7*); and about the present status of and future plans for neutron scattering in the United States (*8, 9*).

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Fundamental Properties of the Neutron

The growth of neutron scattering is firmly rooted in certain fundamental properties of the neutron that impart to it some unique advantages over other commonly used scattering probes. Some characteristics of neutrons, x-rays, and electrons, all with a wavelength of 1 Å, are given in Table 1. For structural studies, in which the goal is to determine the relative positions of atoms within the sample, a probe with wavelength comparable to interatomic distances is desired. Clearly all three probes can be used for structural determinations, with the selection of the most appropriate probe resting on factors other than wavelength. For dynamic studies, in which the goal is to determine the relative motions of atoms within the sample, it is desirable to have a probe with energy comparable to the energy of motion of the atoms in the sample. Because thermally activated motions have energies generally less than 100 meV, the neutron has a great natural advantage for studies of the dynamics of condensed matter.

The relatively slow velocity of thermal neutrons means that easily measured flight times of the order of milliseconds are obtained for distances of a few meters. Thus, time-of-flight techniques are an important part of the total experimental picture in neutron scattering.

There are three important points to be made with regard to neutron scattering amplitudes compared to those of x-rays and electrons. First, the fact that neutrons are relatively weakly interacting (as shown in Table 1) means that multiple scattering effects are less important for neutrons and that measured macroscopic cross sections are more easily interpreted. Second and most important, the nuclear scattering amplitudes for neutrons do not vary systematically across the periodic table as do the corresponding amplitudes for x-rays and electrons. This has important consequences for the ability of neutrons to "see" light atoms in the presence of heavy atoms and to distinguish between neighboring atoms in the periodic table. There is even strong variation in scattering amplitude among isotopes of the same element. The hydrogen-deuterium case is particularly important and is discussed later in connection with applications to biology and polymer science. Finally, the fact that the nuclear interaction between neutrons and nuclei is short range means that the nuclear scattering is isotropic for slow neutrons; there is no form factor as there is in the x-ray case. This has two

important consequences. One is that, in crystallographic studies, the angular dependence of Bragg intensities is directly related to thermal motion and does not require knowledge of atomic form factors. The other is that, in measurements of amorphous materials and liquids, the pair-correlation functions can, in principle, be determined more accurately because the signal is not suppressed at high momentum transfers as a result of a falling off of the form factor.

The neutron's magnetic moment means that, in addition to the nuclear interaction, there is a magnetic interaction with atomic magnetic moments. The magnetic scattering of neutrons has truly revolutionized our understanding of magnetic materials. A large array of complex magnetic structures has been determined, and magnetic scattering has served as a fruitful means of testing theories of phase transitions. The very weak magnetic interaction of x-rays has been demonstrated (*10, 11*) and may be useful for experiments requiring good momentum resolution, but the neutron will remain the probe of choice for most magnetic studies.

The penetration of neutrons (indicated in Table 1 for aluminum) means that neutron scattering is almost always a bulk technique. Experimental results are normally not affected by the condition of the surface. Residual stresses can be probed to depths of several centimeters, and the entire population of defects in a sample can be simultaneously measured. An important consequence of the penetrating power of neutrons is the ease of bringing a beam in and out of cryostats, furnaces, and pressure cells. It is easy to control the sample environment with common structural materials.

Finally, the greatest disadvantage in the use of neutrons is their high cost, compared to photons or electrons, and their relative scarcity. These factors dictate that neutrons be used only for those problems in which their unique properties give them clear advantages over other probes. As discussed in the next section, this constraint still leaves wide fields of research in many scientific disciplines open for the use of neutron scattering.

Table 1. Fundamental properties of condensed-matter probes.

Wavelength (Å)	Energy		Velocity (m sec^{-1})	Magnetic moment (Bohr magnetons)	Scattering amplitude ($\times 10^{-12}$ cm)	Transmission*
	Electron volt	Kelvins				
			Neutrons			
1.0	8.2×10^{-2}	950	4×10^3	10^{-3}	0.1 to 1.0	0.94
			X-rays			
1.0	1.2×10^4	1.4×10^8	3×10^8		0.1 to 20	0.0
			Electrons			
1.0	1.5×10^2	1.7×10^6	7×10^6	1.0	$(0.2 \text{ to } 8) \times 10^4$	0.0

*Transmission through 0.25 inch of aluminum.

Scientific Diversity

Neutron scattering grew up in the hands of solid-state physicists and crystallographers, but in recent years it has been productively applied in many other disciplines. In this brief survey of scientific applications, I pay particular attention to the newer, nontraditional areas of research and mention some of the instruments that have contributed to the current breadth of neutron scattering to convey an overall impression of the versatility of this technique (*12*).

Condensed-matter physics. The study of magnetic materials has always been an important application of neutron scattering. The relative orientation of atomic magnetic moments and the periodicity of the magnetic structure are revealed by the intensities and location of elastic (Bragg) peaks that appear in the diffraction pattern when a material undergoes magnetic ordering. For antiferromagnetic materials, neutron diffraction has been the only method for determining magnetic structures. Contained in the magnetic intensity is the atomic magnetic form factor, which is analogous to the x-ray form factor. Whereas the x-ray form factor is related to the total atomic charge distribution, the magnetic form factor is related to the distribution of magnetic moment. This distribution arises from those electrons outside closed shells, so that the measurement of the magnetic form factor is one of the best techniques for experimental verification of theories of the outer electronic wave functions in solids.

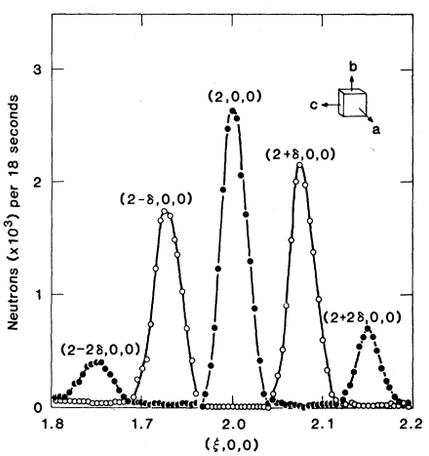

Fig. 1. Polarization analysis of Bragg scattering from a single crystal of manganese phosphide (temperature, 4.3 K; magnetic field strength, 0.7 T). The neutron polarization is along the crystallographic **b** direction. The spin-flip (○) peaks at $(2 \pm \delta, 0, 0)$ indicate that there is a sinusoidally modulated moment along **c** with a propagation vector along **a** of magnitude $(2\ \pi/a)\delta$. The non–spin-flip (●) peaks at $(2 \pm 2\delta, 0, 0)$ indicate a modulated component along **b** with a propagation vector of $(2\pi/a)2\delta$. This is characteristic of a fan phase, in which the moments stay in the *bc* plane and oscillate around the **b** direction as one progresses through the crystal along **a**.

The theory of phase transitions has been a central part of condensed-matter physics in recent years. A fruitful testing ground for theories of phase transitions has been the observation of critical magnetic scattering of neutrons near the transition temperature and of the growth of long-range magnetic order below the transition temperature as revealed by Bragg scattering of neutrons from antiferromagnets (*1*).

The interatomic forces (exchange interactions) responsible for magnetic order can be deduced from measurements of inelastic magnetic scattering of neutrons. Similarly, the interatomic (electrostatic) forces responsible for the mechanical and acoustic properties of matter can be determined through inelastic nuclear scattering of neutrons.

Distinguishing between magnetic and nuclear scattering is a frequent experimental problem when working with magnetic materials. By using a polarized neutron beam and analyzing the polarization after scattering, it is possible to separate clearly the magnetic and nuclear scattering. This technique of polarization analysis is based on the fact that components of the atomic moments parallel to the neutron spin produce non–spin-flip scattering, while components of the atomic moments perpendicular to the neutron spin produce spin-flip scattering. Coherent nuclear scattering (for disordered nuclear spins) will always be non–spin-flip. It is possible to arrange the experiment to measure separately the spin-flip and non–spin-flip cross sections and to ensure that all the magnetic

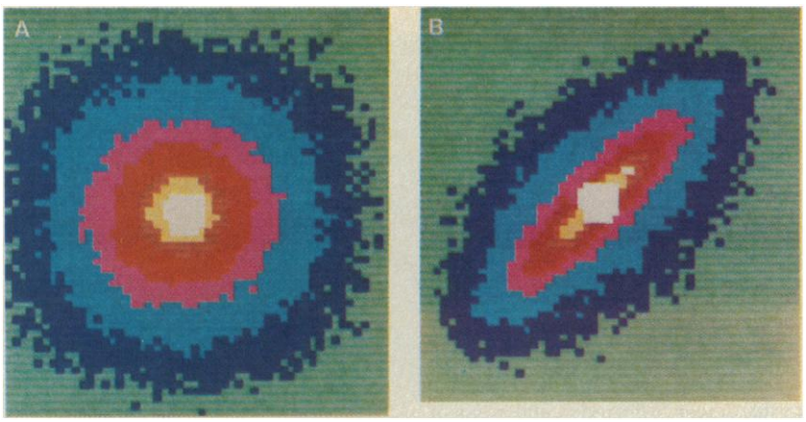

Fig. 2. Color-coded intensity contours from SANS analysis of undeformed (circular contours) and deformed (elliptical contours) polystyrene. The draw direction was parallel to the minor axis of the elliptical contours. The pattern indicates elongation of individual chains along the macroscopic deformation direction. The samples contained 10 percent deuterated polystyrene and were prepared at the University of Massachusetts. The data were obtained at Oak Ridge National Laboratory.

scattering is spin-flip. The technique is also useful for separating coherent nuclear scattering from the incoherent scattering caused by disordered nuclear spins, which is an important distinction in studying liquids and amorphous materials. As shown in Fig. 1, polarization analysis can also be extremely useful in determining complex magnetic structures. This technique has been available for many years but has not been generally applied because of intensity limitations. Recent advances in the production of polarized beams (*7*) and the proposed development of sources with higher flux should result in wider use of this valuable technique.

Biology. As Moore has pointed out in a recent review (*2*), the applications of neutron scattering to biology are closely associated with the scattering properties of hydrogen and deuterium. In electron density maps prepared by x-ray crystallographic studies of biological molecules, the hydrogen atoms are not visible. Because most of these molecules contain more hydrogen atoms than all other atomic species combined, this is an important omission. In fact, the arrangement and exchange of hydrogen atoms and water in biological molecules can often provide a key to understanding biological processes and properties. The original motivation for biologists who entered the neutron field was the ability to conduct high-resolution neutron diffraction studies that would make it possible to determine hydrogen positions in protein structures. The neutron data are used in conjunction with, not in place of, the x-ray data to allow a complete structure determination. To date, about six proteins have been studied by neutron diffraction. In the United States the work is carried out at Brookhaven National Laboratory and the National Bureau of Standards.

In another general area of application, neutrons are used in low-resolution studies to determine the location and shape of molecular components in some larger structures. These low-resolution studies became possible with the development of small-angle neutron scattering (SANS) instruments, which were initially used in Europe, but now also have an important part in research in the United States. Two technological developments came together to promote the growth of SANS: large-area, positive-sensitive detectors and dedicated computers, which make possible the acquisition, organization, and analysis of large amounts of data. The area of the detectors is typically 64 by 64 cm, with a resolution element of about 1 by 1 cm. These instruments can be used to measure the size and shape of objects ranging in size from roughly 10 to 2000 Å.

The SANS pattern is determined by variations in the scattering length density, which for a molecule is simply the sum of scattering lengths for all the atoms divided by the molecular volume. The important feature for biological studies is that the scattering length for hydrogen is -0.37×10^{-12} cm, while for deuterium it is $+0.67 \times 10^{-12}$ cm. Therefore, the scattering length density of water can be changed from -0.55×10^{10} cm^{-2} to 6.36×10^{10} cm^{-2} by mixing H_2O and D_2O. These numbers bracket the scattering length densities for most biological materials, so that it is possible to make any particular material invisible in a SANS experiment by dissolving it in water with the appropriate H_2O:D_2O ratio. This "contrast variation" technique can be applied productively to the study of objects that contain two different chemical species with different scattering length densities. By matching the scattering length density of the solvent to that of species *A*, the shape and size of species *B* can be determined. Similarly, by changing the D_2O concentration in the solvent so that species *B* is invisible, the shape and size of species *A* can be deduced. This technique has been used, for example, in studies on nucleosomes, viruses, and transfer RNA.

It is also possible to use selective deuteration of the material under study to label specific structural subunits and thereby determine the position of these labeled subunits in the larger structure. Important examples are studies of lipids in membrane bilayers and of the positions of proteins in ribosomes.

Polymer science. The SANS technique, coupled with selective deuteration and contrast variation, is also extremely important in a wide variety of polymer experiments (*3*). Polymer scientists constitute the largest group of users of SANS facilities in the United States. One of the earliest and most important applications was the confirmation of Flory's random walk model for the polymer chain configuration in bulk, amorphous material. Small amounts of deuterated polymer were added to a matrix of the same, but fully hydrogenated, polymer; in this way the single-molecule structure factor was measured and found to be in agreement with that of Flory's model.

The state of miscibility in polymer blends (alloys) can be characterized by SANS, and this information has been particularly valuable in view of the current interest in producing new materials from blends of available polymers. Before the development of the SANS technique, the methods used to investigate the compatibility of polymers in blends could indicate macroscopic segregation but could not detect fine-grained separation at the level of molecular segments. SANS data from blends in which a fraction of one polymer species has been labeled with deuterium reveal compatibility at the segmental level as measured by the Flory interaction parameter and provide information on chain configuration in the blend.

Block copolymers contain two or more chemical subchains within a single

polymer chain. These subchains can separate into microphases as a result of mutual incompatibility of the different parts of the molecule. Such microphase regions are compact, each containing parts of many molecules and giving a colloidal-type structure with a characteristic dimension of about 100 Å. SANS studies have revealed the structure of these microphase regions along with the individual chain dimensions within the microdomains.

Because of the random chain configuration of amorphous polymers, the SANS patterns are normally circularly symmetric around the incident beam. Macroscopic deformation of polymer samples can stretch chains in a preferred direction, resulting in anisotropic SANS patterns. An example of this effect is shown in Fig. 2. The anisotropy was induced by extruding the polymer at a temperature above the glass-transition temperature and then quenching to room temperature.

Polymer dynamics is an active area of study at ILL, where the combination of abundant cold neutrons and special instruments with extremely good energy resolution makes these studies possible. This capability does not now exist in the United States.

Chemistry. The first chemical application of neutron scattering was by crystallographers who used neutron diffraction to locate light atoms, particularly hydrogen, in a wide variety of structures. Much of this work requires single crystal samples, but in recent years powder diffraction has become a useful technique for moderately complex structures. A contributing factor to the growth of powder techniques has been the success of the Rietveld data analysis method, in which each data point of a powder pattern is a separate input to a complex least-squares analysis program. With the current generation of high-resolution neutron powder diffractometers, refinement of structures with up to 100 adjustable parameters can be achieved.

Although high-resolution powder instruments are available at reactor sources, the technique is particularly effective with pulsed neutron sources, where the experimental variable is the neutron wavelength rather than the scattering angle. The diffraction pattern is sorted by time-of-flight, which results in good resolution at very small *d* spacings. An example obtained at the Intense Pulsed Neutron Source (IPNS) at Argonne National Laboratory on lithium-stabilized sodium β″ alumina is shown in Fig. 3. In this system a small amount of lithium dopant favorably modifies the ionic conductivity of Na^+. Jorgensen and colleagues (*13*) performed the experiment to identify the site of the lithium defect and to determine the resulting modifications in the sodium conduction plane.

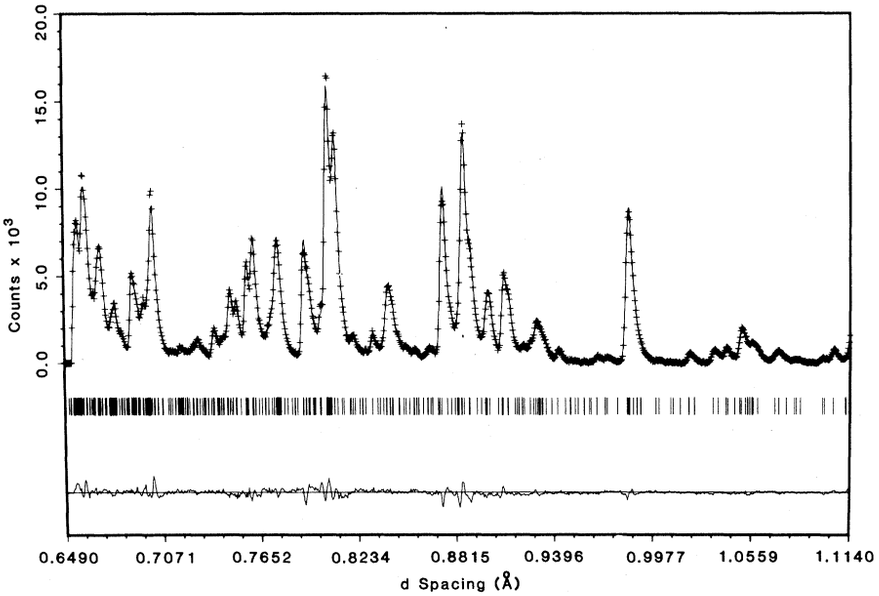

Fig. 3. A portion of the raw time-of-flight powder diffraction data (+) and the least-squares fitted profile (continuous line) for lithium-stabilized Na^+ β″ alumina at 12 K. Tick marks below the data indicate the positions of allowed Bragg reflections included in the fitting procedure. A difference (observed minus calculated) curve appears at the bottom.

Submicrometer or colloidal systems have long been an area of industrial importance, and most research has traditionally concentrated on the macroscopic behavior of these systems. In recent years the SANS technique has been remarkably useful in studying the microscopic properties of such systems. Not only can details of the intraparticle structure be studied, but interparticle correlations in position are revealed. In fact, these systems form three-dimensionally ordered arrays of particles.

Surfactant solutions form a rich variety of submicrometer structures that vary with temperature and concentration. These include spherical and cylindrical micelles; lamellar, cubic, and hexagonal structures; and liquid-crystalline phases. Advances in liquid theory have made possible a quantitative description of scattering from spherical micelles or colloids in concentrated solution, with excluded volume, coulombic, or magnetic dipolar interactions between the particles. Attention is now turning to the anisotropic phases. Anisotropic SANS scattering from cylindrical micelles aligned by viscous shear has recently been observed and analyzed.

Catalytic materials are also being investigated with various neutron scattering techniques. Powder diffraction is being used to study the structure of zeolites, and inelastic scattering is being used to study proton siting and mobility as the zeolite temperature approaches that used in chemical processing. Inelastic studies have also been performed on adsorbed molecular species on fine particles of platinum and nickel.

Chemical spectroscopy through inelastic neutron scattering is a rapidly growing field in Europe, largely because of the good energy resolution available on some of the ILL spectrometers. Rotational energy levels in solids, diffusion, and relaxation phenomena are particular focuses of this work.

Materials science. There are great although still largely unrealized opportunities for application of neutron scattering to materials science. Many of these opportunities stem from the penetrating power of neutrons, which permits observations of bulk rather than surface properties of microstructure and defects and allows scattering studies to be performed on samples within furnaces, cryostats, and pressure cells. The study of changes in microstructure during the processing of alloys and ceramics is perceived as an area of great potential. Another developing area is real-time studies of structural responses to external perturbations such as temperature, stress, electrical fields, and magnetic fields. Either periodic or stepwise perturbations can be applied. Position-sensitive detectors covering

Table 2. Current U.S. neutron sources for neutron scattering experiments: reactors.

Facility	Date of criticality	Power (MW)	Thermal flux*	Instruments (No.)
High-Flux Isotope Reactor (*16*)	1965	100	10	9
High-Flux Beam Reactor (*17*)	1965	60	9	11
National Bureau of Standards reactor (*18*)	1967	20	2	9
Missouri University research reactor (*19*)	1966	10	1	7
Massachusetts Institute of Technology reactor (*20*)	1958	5	1	6
Rhode Island Nuclear Science Center (*21*)	1964	2	0.14	2

*Approximate flux at entrance of beam tubes (neutrons per square centimeter per second $\times 10^{14}$).

large scattering angles and high neutron fluxes are needed for these studies.

Many problems in materials science are concerned with damage accumulation in various forms—for example, microcracking, grain boundary cavitation, and radiation damage. The SANS technique is an excellent one for studying such defects. An example of SANS data from microcracks in the ceramic material yttrium chromite is shown in Fig. 4. Microcracks are induced in this material by annealing at temperatures greater than 1100°C and can be healed by annealing below this temperature. Porosity and grain size remain unchanged by anneals near 1100°C, so that the difference in SANS data for patterns annealed above and below this temperature gives the scattering from the microcracks. Modeling the microcracks as randomly oriented thin disks gives an excellent fit to the data and yields the mean crack opening displacement and crack number density.

The penetrating power of neutrons allows bulk, nondestructive studies to be made of manufactured components. For example, the texture (preferred orientation of grains) and residual stress can be measured as a function of distance below a surface.

The nonperiodic variation of nuclear scattering lengths opens up a variety of experiments in alloy behavior. For example, the coherent scattering lengths of manganese, iron, and cobalt are -0.37×10^{-12}, $+0.95 \times 10^{-12}$, and $+0.25 \times 10^{-12}$ cm, respectively. Because these elements are consecutive in the periodic table, their x-ray scattering lengths are nearly the same. Even greater opportunities emerge when isotopic substitution is considered. The neutron scattering lengths for various isotopes of nickel range from -0.87×10^{-12} to $+1.44 \times 10^{-12}$ cm. This behavior allows studies of order-disorder phenomena, clustering, and phase decomposition that may not be possible with x-rays.

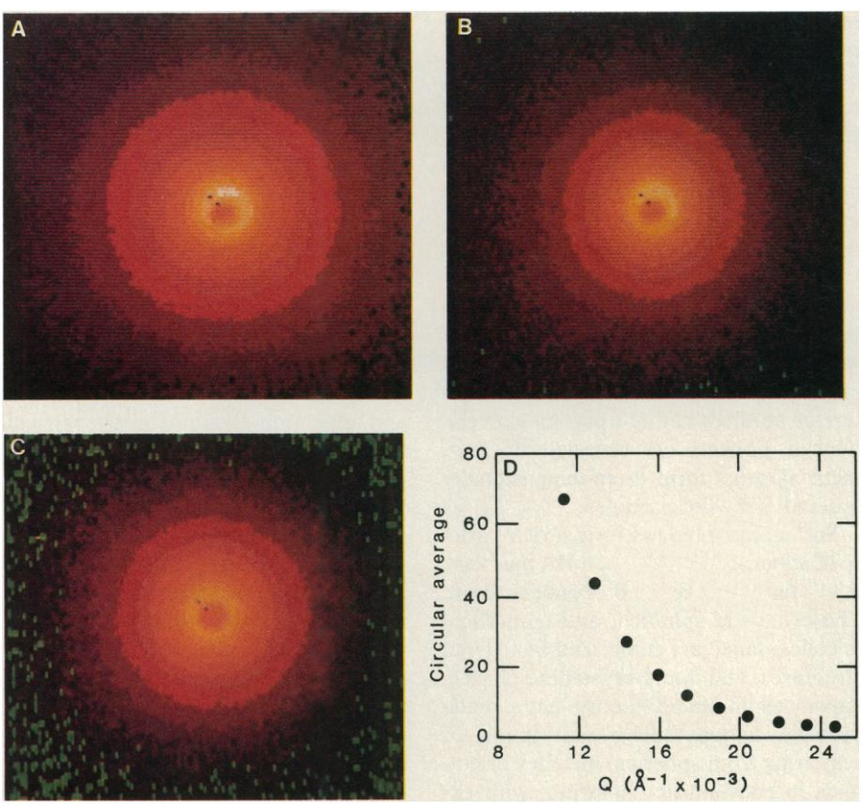

Fig. 4. The small-angle neutron scattering from a specimen of the ceramic yttrium chromite, recorded on a two-dimensional neutron detector. The scattering is presented in color contour plots in which the scattered intensity is mapped to the colors of a black-body spectrum. In (A) some of the scattering is due to microcracks that result when the sample is cooled through a phase transition at roughly 1110°C. The pattern in (B) was obtained after annealing the specimen at 1000°C to heal the microcracks. The difference in (C) is therefore the scattering from the microcracks alone (green dots denote negative values resulting from the subtraction). This net scattering, circularly averaged, is plotted against momentum transfer, Q, in (D). The data were obtained at the National Bureau of Standards (*15*).

User Community in the United States

Neutron scattering grew up around research reactors constructed at the national laboratories for purposes associated mostly with the development of atomic energy. Small groups of scientists at these laboratories enjoyed a near monopoly on the use of this technique. Outside scientists were not excluded, but neither were they encouraged in any organized fashion. It was not until 1979 that the U.S. Department of Energy adopted a policy aimed at increasing the use of these facilities by outside scientists (they would not be charged for beam time, provided they published their results). Since that time, partly because of this policy and partly because of the commissioning of SANS facilities at several reactor centers and the opening of Argonne's IPNS, the number of U.S. users of neutron scattering facilities has increased to more than 500. This growth is documented in the report of the National Research Council's Panel on Neutron Scattering (*8*).

The present distribution of U.S. users

by sponsoring institution is as follows: universities, 60 percent; federal laboratories, 30 percent; and industry, 10 percent. The scientific diversity is clearly shown by the distribution according to scientific discipline: condensed-matter physics, 35 percent; chemistry, 23 percent; materials science, 16 percent; polymer science, 13 percent; and biology, 13 percent. The nonphysics disciplines have shown the most rapid growth in recent years, and this trend is expected to continue. A healthy sign for the future is that the number of students using neutron scattering facilities has increased sharply in recent years. All neutron scattering centers in this country have active user programs, and they welcome inquiries and proposals.

Table 3. Current U.S. neutron sources for neutron scattering experiments: pulsed sources.

Facility	Date started	Proton energy (MeV)	Average current (μA)	Frequency (Hz)	Instruments (No.)
Los Alamos Neutron Scattering Center (*22*)	1985	800	100	12	5
Intense Pulsed Neutron Source (*23*)	1981	500	12	30	7

Present Facilities and Future Plans

The two most common types of neutron sources for scattering experiments are reactors, in which excess neutrons are produced in the fission reaction and accelerator-based spallation sources, in which protons at high energy bombard heavy nuclei and shake loose neutrons. In both cases, the initially fast neutrons are slowed by inelastic collisions with molecules in a moderator (for example, H_2O or D_2O), and beams of slow neutrons are extracted through tubes penetrating into or near the moderator. As the neutrons are moderated, they approach thermal equilibrium with the molecules of the surrounding medium so that their energy distribution is close to the Maxwell-Boltzmann distribution for the temperature of the moderator. These are the so-called thermal neutrons, with energies close to those of the air molecules we breathe. This thermalization process is less complete in moderators of spallation sources, and the beams are richer in higher energy neutrons. This is one of the major differences between reactor sources and spallation sources. Another major difference is that the proton accelerator at a spallation source is usually operated in a pulsed mode so that bursts of neutrons are produced. These neutron pulses typically may have a time width of 25 μsec and a repetition rate of about 100 Hz. Thus, time-of-flight techniques are commonly used with pulsed spallation sources.

The current U.S. neutron sources that have active neutron scattering programs are listed in Tables 2 and 3. The reactor sources will all soon be 20 years old, and they will be 30 years old before new reactors can replace them. Most of the recent capital investment has gone into the pulsed facilities at Argonne and Los Alamos, but it is not true that these are new facilities. Both were built inexpensively, mostly with existing equipment and buildings.

The most powerful U.S. reactors, the High-Flux Isotope Reactor (HFIR) at Oak Ridge and the High-Flux Beam Reactor (HFBR) at Brookhaven, have thermal flux comparable to that of the ILL reactor in Grenoble. However, they lack the extensive cold neutron facilities that have made the ILL reactor such a valuable asset. Mounted in the reflector at ILL is a cold source of liquid D_2 that slows the thermal neutrons down to even lower energies. Neutron beams are extracted from this cold source through rectangular tubes of flat glass coated with nickel on the inside. The cold neutrons are completely reflected from this nickel surface and thus may be transmitted long distances from the reactor with little loss of intensity. These so-called neutron guides are used to transport cold neutrons into a guide hall, which is a large building adjacent to the reactor building where beam experiments with cold neutrons are performed. The neutron guides are also used, although less effectively, to transport thermal neutrons into the guide hall. This arrangement results in a large increase in the floor space available for experimental apparatus and allows experiments to be performed in a region of low background radiation. European scientists have also been ingenious in devising instruments to use cold neutrons, particularly instruments with good energy resolution. In the United States it is difficult to achieve energy resolutions better than 2×10^{-5} eV, whereas resolutions of 10^{-8} eV are obtainable at ILL.

Existing U.S. facilities are being upgraded so that cold neutron capabilities can be improved. A cold source is now being assembled at the National Bureau of Standards reactor, and there is a proposal to build a guide hall and a number of cold neutron instruments to exploit fully this cold source. The only reactor cold source in the United States is at HFBR at Brookhaven. There is also a proposal to build a guide hall and new instrumentation at HFBR to make better use of this cold source. In the Brookhaven proposal, both cold and thermal beams would be transported to the guide hall. A National Research Council committee appointed to establish priorities in the construction of major facilities for materials research has given guide hall construction the highest priority among proposals to improve existing facilities (*9*).

A major improvement to the pulsed source at Los Alamos is nearing completion. This is a storage ring to accumulate proton pulses from the Los Alamos Meson Physics Facility (LAMPF) into pulses with a time structure appropriate for neutron scattering. In terms of neutron production, the Los Alamos Neutron Scattering Center (LANSCE) will then be competitive with the spallation neutron source (SNS) now becoming operational at the Rutherford-Appleton Laboratory in Great Britain. To make LANSCE fully competitive, an expansion of the experimental hall surrounding the target is needed. A proposal for such an expansion, including construction of several new neutron scattering instruments, has been prepared and was also given high priority by the National Research Council committee. At Argonne's IPNS-1, which has been the world leader among pulsed sources, a cold source has recently become operational, and it is expected that cold neutron research will eventually become as important for pulsed sources as for reactors.

Realization of the proposals outlined above will partially close the gap that has developed between the United States and Western Europe; without these improvements, the United States will surely fall even further behind. Regaining the leadership role will require the construction of a new facility with significantly higher flux. The choice between a new reactor or a new pulsed source is difficult because there is no single figure of merit by which the scientific productivity of the two sources can be compared. Rather, a detailed evaluation of many differ-

ent experiments must be undertaken. Such an evaluation was attempted at a recent workshop held at Shelter Island, New York (*14*). The comparison was between a steady-state source with thermal flux of 5×10^{15} n cm^{-2} sec^{-1} and a pulsed source with a time-averaged thermal flux of about 5×10^{14} n cm^{-2} sec^{-1}. The extensive use of time-of-flight techniques for the pulsed source makes it possible to use a significantly larger wavelength band than in the steady-state case, so that the disparity in time-averaged flux can be overcome in many experiments. No clear advantage for all types of experiments was found for either source. Rather, there were special areas in which one source or the other was most valuable, and there was a large area of overlap in which the two types of sources were roughly comparable. Significantly, cost factors were not considered at this workshop, but cost probably favors the reactor source, particularly with regard to operating cost. The National Research Council committee has given high priority to the design and construction of a new steady-state source, calling for an immediate site-independent design effort. Such an effort is under way at Oak Ridge National Laboratory, where the goal is to produce a design for a reactor with a thermal flux of at least 5×10^{15} n cm^{-2} sec^{-1}. About 30 modern neutron scattering instruments will be included, with a strong emphasis on cold neutron capability. This facility, to be called the Center for Neutron Research (CNR), would be similar to ILL in scope but will have about four times the thermal flux. With improved neutron delivery systems, it is estimated that, for most experiments, the flux on the sample will be at least ten times higher than the flux at HFIR or HFBR. When coupled with the increased number of instruments, the scientific productivity of CNR should be about 30 times that of the best current U.S. neutron sources.

While CNR would ensure that the United States will have superb neutron scattering facilities well into the next century, there is one important part of the European picture that will be difficult to duplicate. I refer to the large number of smaller neutron scattering centers which exist in Europe (*4*) and which have been responsible for most of the innovative new ideas on instrumentation that have then been fully developed at ILL. In this regard, the status of U.S. university reactors becomes a national concern; they should be nurtured and conserved as any other national asset.

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