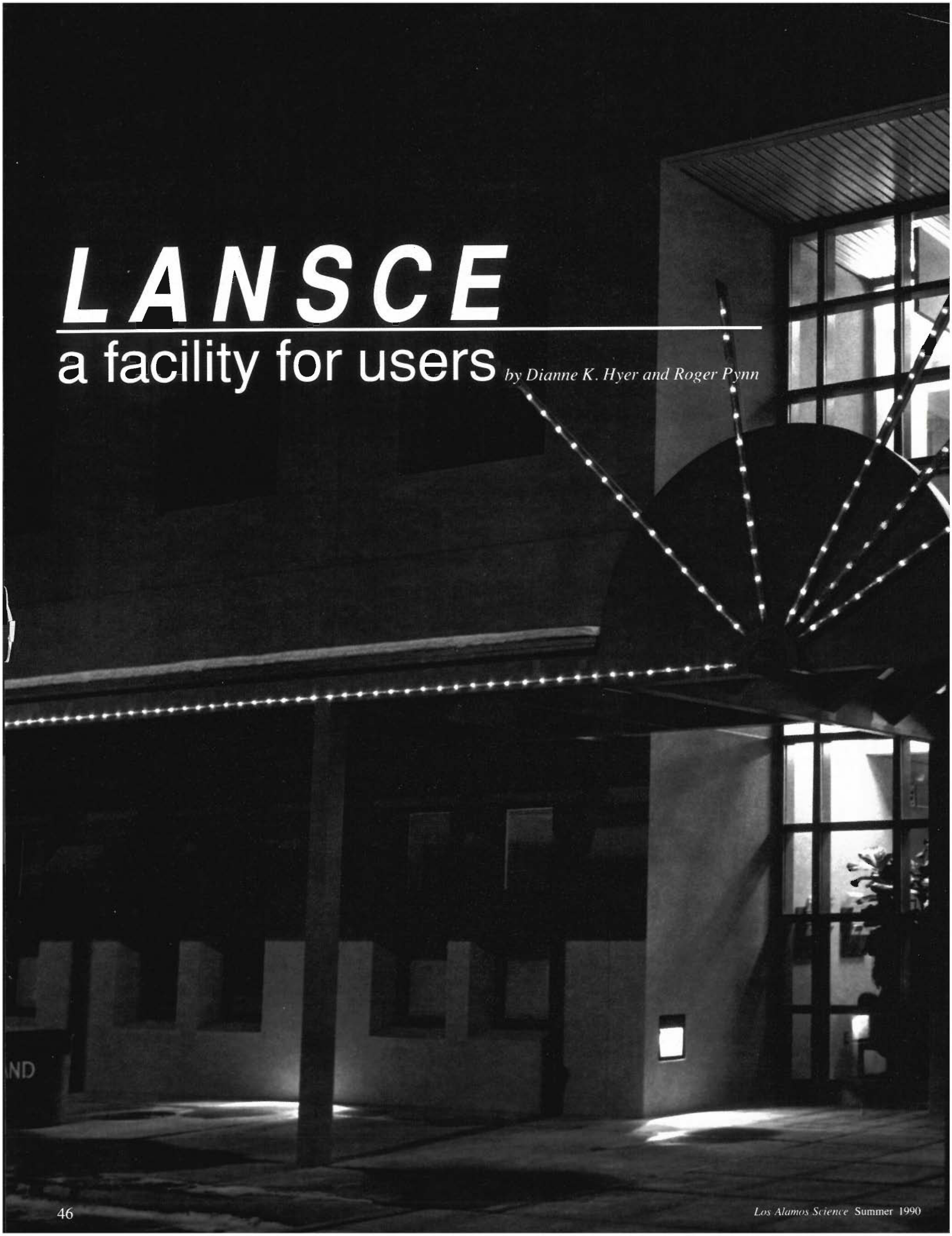
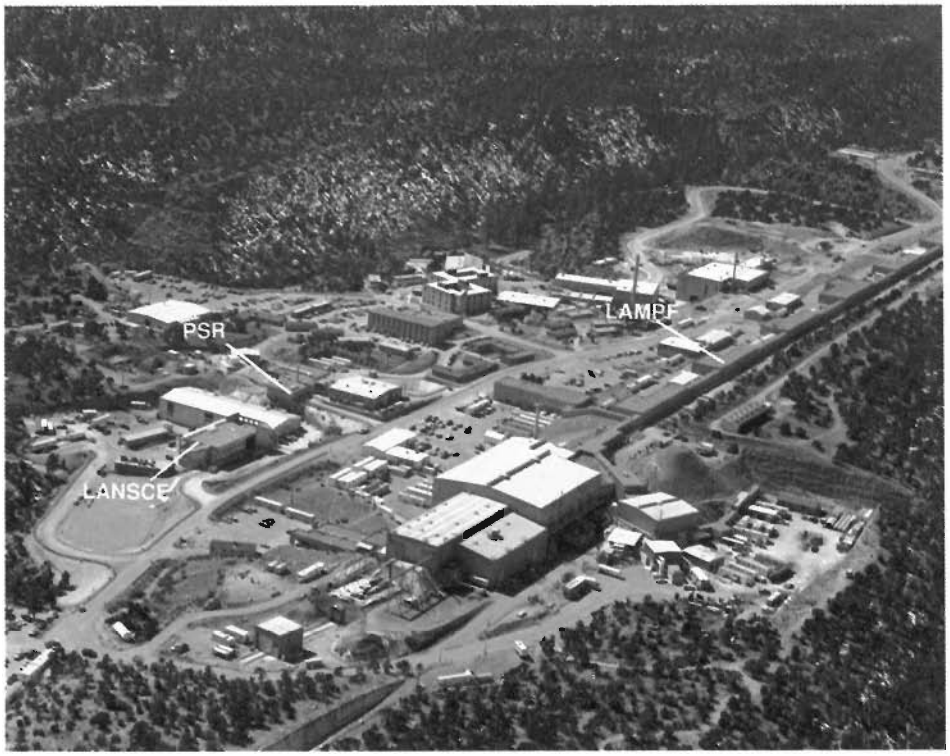
LANSCE
a facility for users

by Dianne K. Hyer and Roger Pynn



Most facilities for neutron-scattering experiments are based at nuclear reactors, but the Manuel Lujan, Jr. Neutron Scattering Center (or, less formally, LANSCE) is one of a new generation of neutron sources that has become available during the past decade—those based at proton accelerators. The new accelerator sources have several advantages. First, an accelerator source does not involve nuclear fission and therefore poses no threat of runaway operation that might lead to dispersal of hazardous radiation. Safe operation of a reactor requires complex control mechanisms, and, as evidenced by the Chernobyl disaster, accidents involving nuclear reactors can cause widespread harm to people and the environment. The cost of reducing the probability of such accidents to a level society finds acceptable is rapidly becoming prohibitive. A second advantage of an accelerator source is that it produces pulses of neutrons, which can be used much more efficiently than the continuous flow of neutrons provided by a reactor. Thus, although the average neutron flux from a pulsed neutron source may be 1000 times smaller than that from a reactor, the pulsed source is capable of producing neutron-scattering results of the same caliber as the reactor. A lower neutron flux means a lower heat-removal load. For example, only 100 kilowatts of heat have to be removed from the LANSCE pulsed source, whereas 500 times more heat must be removed from a comparable reactor source. Finally, with today's technology we could build an accelerator source that provided 100 times more neutrons than the best source of this type currently operating. In contrast, the best reactor we could build would generate only five to ten times more neutrons than existing reactors; any further improvement would require technology beyond today's dreams. LANSCE is thus of interest not only for the tools it currently provides to users but also as an inspiration for future directions in neutron scattering.



This aerial view of Technical Area 53 shows the proton linear accelerator of the Los Alamos Meson Physics Facility, which produces high-intensity pulses of protons for research in medium-energy physics; the Proton Storage Ring, which converts some of the LAMPF pulses into higher-intensity proton pulses; and LANSCE, where those proton pulses are used to create high-intensity pulses of neutrons for research in materials science.

History

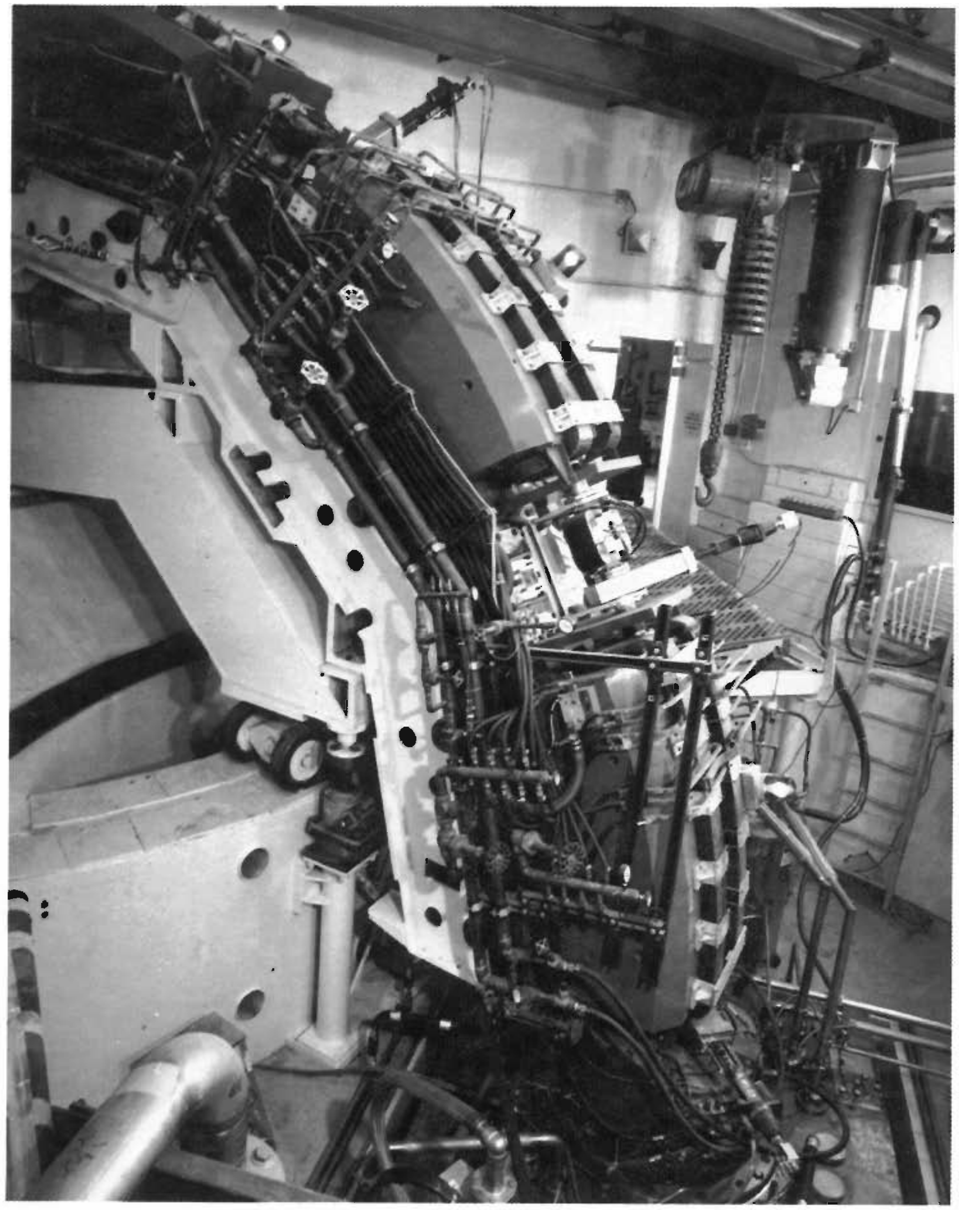
The origins of the Los Alamos high-intensity pulsed neutron source and user program go back to the 1960s when new accelerator technology culminated in the building of the Los Alamos Meson Physics Facility (LAMPF)—a linear accelerator providing 1-milliampere pulses of 800-MeV protons at a repetition rate of 120 per second. Then in the early 1970s the Weapons Neutron Research (WNR) facility was built as an adjunct to LAMPF. The WNR facility gave the Laboratory an intense neutron source that could be used to obtain nuclear data needed for weapons design.

The original plan for the WNR facility included a unique feature—a 30-meter-diameter ring, called the Proton Storage Ring (PSR), into which a series of proton pulses from LAMPF could be injected. Each injected pulse was to occupy about three-quarters of the ring's circumference. Several thousand proton pulses were to be "overlaid" within the ring, ejected as one high-intensity pulse several times per second, and used to produce neutrons by spallation—a nuclear reaction in which neutrons are knocked out of heavy nuclei by energetic subatomic particles. The Department of

Energy weapons-funding agency accepted a proposal to fund the WNR facility in two phases. The first phase included construction of the proton-beam-transport system and the spallation-target area. The ability of a storage ring to produce high-intensity bursts of protons—which in turn would produce high-intensity bursts of neutrons—was recognized, and plans were made to build the PSR in the second phase.

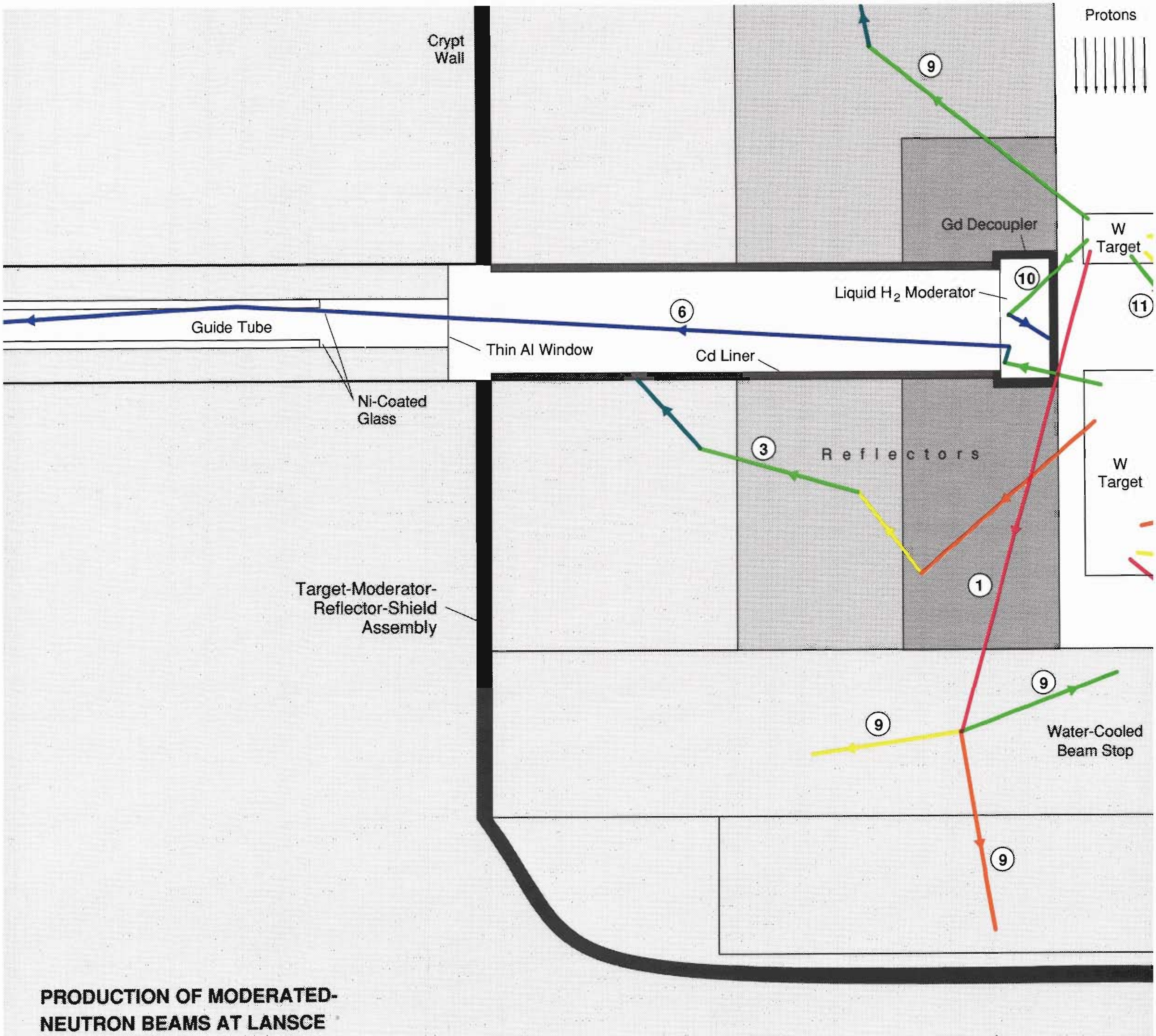
The late Rex Fluharty recognized that the WNR facility had great potential for materials-science research in addition to the nuclear-physics research that had justified the initial funding. Consequently, it was designed as a multi-user facility to serve both scientific communities—nuclear physics, with neutrons of keV energies, and materials science, with neutrons of meV energies. The WNR facility produced neutrons for the first time in May 1977, and routine operation ensued the following year. Shortly thereafter, the Laboratory administration, spurred by George A. Keyworth (then leader of the Physics Division) sponsored the idea of making the WNR facility a national user facility for materials-science research.

In the early 1980s various national scientific committees advised expansion of the WNR experiment area to facilitate hosting a national user program in neutron scattering. The committees also urged that the nuclear-physics and neutron-scattering programs be provided separate neutron-producing targets so each might be optimized. Those recommendations led, in October 1986, to designation of the existing WNR facility as a national facility for neutron scattering. Shortly thereafter funds were made available for construction of a large addition to the experiment hall, a support building containing laboratories and office space, and several new neutron spectrometers. At the same time a new facility was constucted for nuclear-physics experiments. The expanded materials-science facility was called the Los Alamos Neutron Scattering Center; it was later renamed the Manuel Lujan, Jr. Neutron Scattering Center in honor of long-term New Mexico Congressman Manuel Lujan, Jr.



A series of bending magnets guides high-intensity proton pulses from the Proton Storage Ring to the LANSCE spallation target.

The basic experimental methods at spallation sources involve the creation of discrete but intense pulses of low-energy neutrons and subsequent measurement of neutron times of flight to determine neutron energies. To understand both the principles of those processes and the technology required for their implementation, we will track a few neutrons from their "birth" in the



PRODUCTION OF MODERATED-NEUTRON BEAMS AT LANSCE

Fig. 1. This vertical section through the LANSCE target assembly and bulk shield illustrates the hardware and the processes involved in the production of pulsed beams of moderated neutrons. A pulse of spallation neutrons is created when a pulse of 800-MeV protons impinges on the tungsten targets. Some of the spallation neutrons collide with nuclei in moderators or reflectors; their trajectories (arrows) thereby change direction, and their energies (represented by various colors) decrease. The numbered trajectories illustrate points of particular importance.

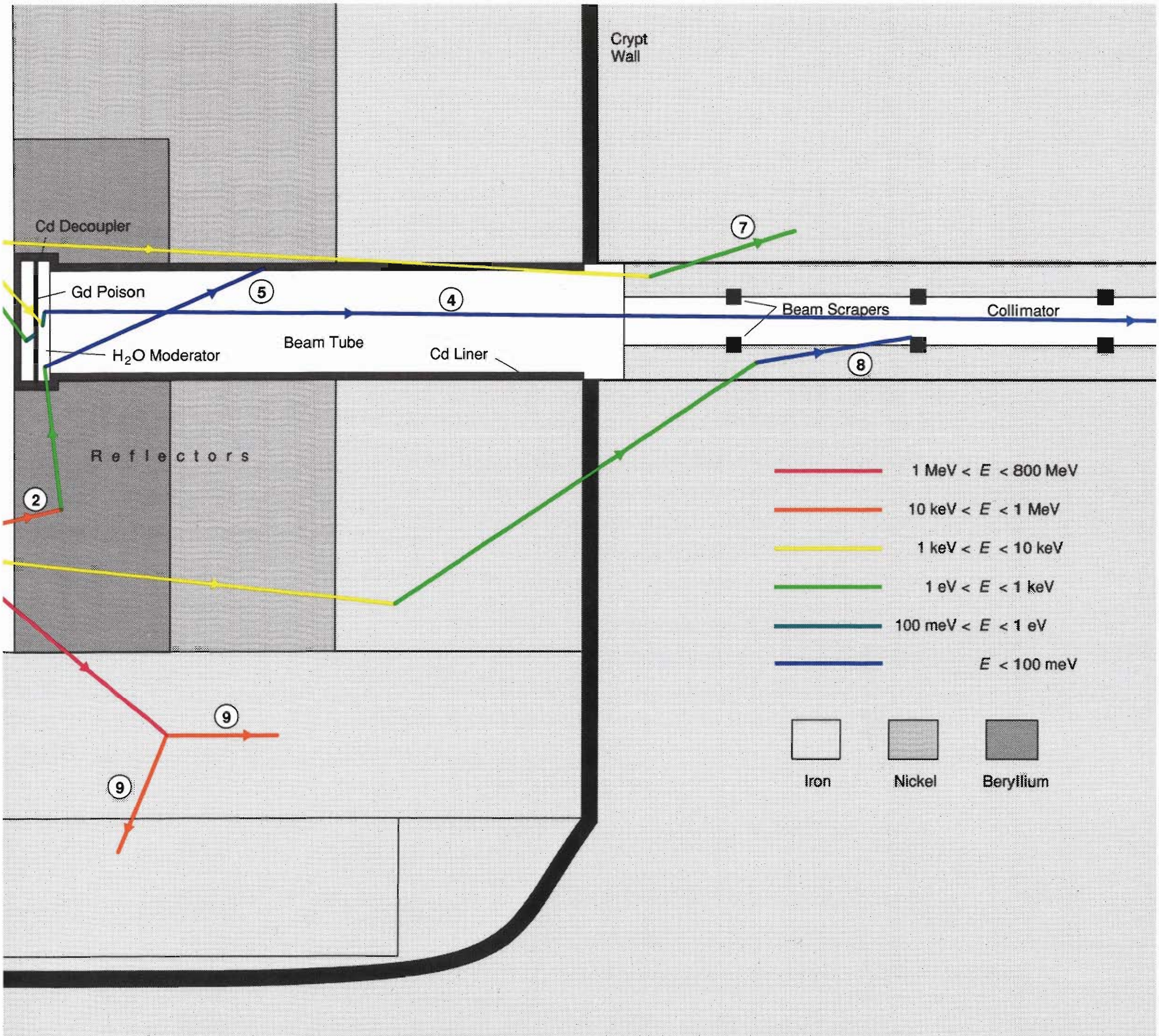
1. Very-high-energy spallation neutrons leave the target moving roughly in the same direction as the incident proton beam. Such neutrons can generate lower-energy spallation neutrons in the reflectors, the beam stop, and the surrounding shield.

2. Neutrons whose initial trajectories miss a moderator may be scattered into a moderator by a beryllium reflector.

3. Neutrons that reach low energies by wandering around in the reflectors for a long time are prevented from entering a beam tube by a liner made of cadmium, which absorbs low-energy neutrons.

4. Some thermal neutrons exit the moderator along trajectories that pass through a beam tube and a collimator. Note that the neutron depicted was not absorbed by the cadmium decoupler on the back face of the moderator because of its high initial energy.

5. Thermal neutrons that leave the moderator traveling at large angles relative to the axis



of a beam tube are absorbed by the cadmium walls of the tube.

6. Thermal neutrons that strike a wall of a guide tube at sufficiently small angles are reflected by the tube's nickel coating and therefore proceed down the tube being reflected from opposite sides of the guide tube walls. Such neutrons would have been lost by absorption in the walls of a collimator.

7. The iron walls of the collimator scatter epithermal neutrons and thereby define the size of the epithermal-neutron beam that exits the collimator.

8. Beam scrapers made of boron carbide absorb thermal neutrons that leak into the collimator and thereby help define the thermal-neutron beam that exits the collimator.

9. Most of the spallation neutrons are never used in an experiment because they are lost in the shielding around the target.

10. Thermal neutrons whose trajectories would allow them to exit the back face of a moderator are absorbed by the gadolinium decoupler, thus eliminating crosstalk between moderators by ensuring that each moderator feeds only one beam tube.

11. A thin slab of gadolinium poison reduces the thickness of the moderator feeding thermal neutrons to the beam tube and thereby reduces the duration of the thermal-neutron pulse.

spallation target, through their scattering in a sample, to their "death" by absorption in a neutron detector.

The LANSCE Source

Figure 1 shows a vertical cut through the target assembly that generates pulsed neutron beams at LANSCE. The neutron beams emerge into the experiment area from beam tubes joined to holes drilled horizontally through a radiation shield surrounding the crypt—an evacuated steel vessel that holds the target, moderators, and reflectors. Pulses of high-energy (800-MeV) protons from the PSR enter the crypt from above and impinge on the spallation target.

The LANSCE target, a so-called split target, is composed of two 10-centimeter-diameter cylinders of tungsten. The high-mass—and, therefore, neutron-rich—nuclei of tungsten have a high cross section for spallation. Each of the approximately 10^{13} protons per pulse produces an average of 19 spallation neutrons, which have energies ranging from almost zero to nearly 800 MeV. Because neutron-scattering experiments require neutrons with energies below about 1 eV, the spallation neutrons must be reduced in energy, or moderated, before being directed toward a sample. The moderation is accomplished by allowing the neutrons to collide with light nuclei, such as hydrogen, to which they can transfer a substantial fraction of their kinetic energy.

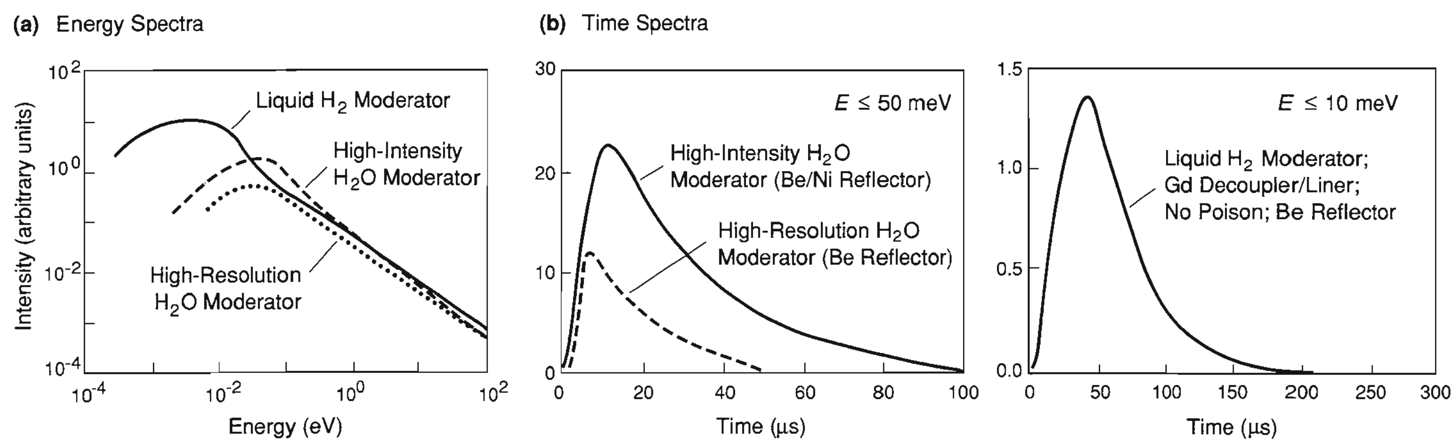
The LANSCE crypt contains four moderators to reduce the energies of the spallation neutrons. One is filled with liquid hydrogen and the others with room-temperature water. (Only two of the LANSCE moderators are shown in Fig. 1; the other two would appear in cross sections other than the one depicted.) The energy spectrum of the neutrons emerging from a moderator depends on the temperature, composition, and thickness of the moderator. For example, as shown in Fig. 2a, a water moderator yields a spectrum that peaks at about 25 meV, whereas the liquid-hydrogen moderator yields a spectrum that peaks at about 5 meV. The space within the crypt not occupied by the targets and moderators is largely filled with beryllium and nickel reflectors. These materials scatter some neutrons back into the moderators, giving them a second chance to lose energy and to emerge along a beam tube. (Only two of the current sixteen LANSCE beam tubes appear in Fig. 1.)

Figure 1 also shows possible events in the lives of a few spallation neutrons as they are scattered in the moderators and reflectors. When a neutron suffers a collision, both its trajectory and its energy change. Such changes are indicated in the figure by changes in the direction and color of the arrows representing moving neutrons. Most of the neutrons born with energies above 20 MeV start life moving in directions not much different from the trajectory of the proton beam. Less energetic neutrons emerge from the targets more or less isotropically. Some neutrons pass directly into one of the moderators and, after losing energy there, exit from the moderator along a beam tube. Other neutrons are reflected into the moderators by collisions with nuclei in the reflectors. The highest-energy neutrons can induce spallation of nuclei in the reflectors, beam stop, or shielding; that process is indicated in Fig. 1 by emergence of two or more neutrons from a vertex. Some of the secondary spallation neutrons produced by the high-energy neutrons find their way back to the moderators and end up traveling along a beam tube.

The few neutron histories depicted in Fig. 1 clearly show that the moderated neutrons arising from a proton pulse exit a moderator at different times, even though the proton pulse is extremely brief (270 nanoseconds). After all, the paths along which various neutrons travel differ as do their velocities. Therefore, the duration of the pulse of moderated neutrons is much greater than that of the proton pulse (Fig. 2b). Furthermore, it increases as the average energy of the neutrons decreases. One qualitative feature of the neutron pulse is independent of energy, however: its asymmetry. As Fig. 2b shows, the pulse reaches its peak intensity very quickly and then decays more slowly.

The speed, and hence energy, of an individual neutron can be determined accurately from its time of flight (that is, the time taken by the neutron to travel from a moderator to a detector) only if the time at which the neutron left the moderator is known accurately. Thus, a short neutron pulse allows time of flight to be determined with high relative accuracy. Unfortunately, the pulse duration can be reduced only at the expense of decreased neutron intensity. Thus increasingly accurate time-of-flight measurements are accompanied by increasingly greater statistical errors in the measured neutron scattering law.

What is to prevent neutrons that have been moderated by wandering around for a long time in a reflector from leaking into a beam tube? Such leakage would clearly extend the duration of the neutron pulse and degrade the accuracy of time-of flight measurements. Closer examination of Fig. 1 shows that some low-energy neutrons stop at the wall of a beam tube, whereas more energetic neutrons keep right on going. That is so because the beam tubes are lined with a material, such as cadmium or boron carbide, that captures low-energy neutrons but does little to stop the more energetic ones. A similar neutron-absorbing material—a "poison"—placed inside a moderator reduces the effective thickness of the moderator for thermal neutrons and thereby reduces the duration of the thermal neutron pulses. The closer the poison is to the exit face of the moderator, the



CHARACTERISTICS OF LANSCE NEUTRON PULSES

Fig. 2. (a) The energy spectrum of the neutron pulses emerging from any of the LANSCE moderators is very broad. Details of the spectrum vary with the composition, temperature, and thickness of the moderator. Note the relatively small difference between the energy spectra of neutrons from the high-intensity water moderator and from the high-resolution water moderator. (The primary physical difference between those moderators is the location of the poison.) (b) The time spectrum of the LANSCE neutron pulses is asymmetric and much broader than the time spectrum of the proton pulses, which has a full width at half maximum of 0.27 microseconds. Like the energy spectrum, the time spectrum varies with the composition, temperature, and thickness of the moderator. Location of the poison in the high-resolution water moderator closer to the exit face decreases the FWHM of the time spectrum and thereby increases the accuracy of the time-of-flight (and thus energy) measurements. However, the increased accuracy in energy is bought at the price of lower intensity and hence greater statistical uncertainties in the measured signal.

shorter is the neutron pulse and the lower its intensity. The location of the poison is the feature that primarily distinguishes the two "high-intensity" water moderators at LANSCE from the single "high-resolution" water moderator. (The liquid-hydrogen moderator contains no poison.)

Figure 1 illustrates another important point: Production of moderated neutrons is extremely wasteful. Most of the spallation neutrons wander off into the reflectors and the shielding without ever encountering a moderator or a beam tube. By changing the relative arrangement of the various moderator, reflector, and neutron-absorbing materials, it is possible to increase somewhat the neutron flux emerging from the moderators. For example, the LANSCE split target yields a higher neutron flux than a single target because it simultaneously feeds neutrons into the moderators from above and below. We are fortunate to have access at the Laboratory to the best computer codes—not to mention a few Crays—to optimize the configuration of the target assembly. The optimization cannot be performed analytically; Monte Carlo computations are the only recourse for tracking neutrons and improving the performance of spallation neutron sources.

The LANSCE split target is unique worldwide, thanks to the conceptual design of Gary Russell and his colleagues. The assembly was installed in August 1985 and has since operated reliably with no target or moderator changes. What makes the LANSCE source so special is that it is very efficient and very "clean": efficient because the moderators are fed with neutrons by both the upper and lower targets, and clean because only a small fraction of the spallation neutrons escape along a beam tube without first being moderated. The latter point is important because unmoderated neutrons, which are not useful for neutron scattering, degrade experimental results by contributing background signals. More important, high-energy neutrons can damage living cells and are better kept within the crypt.

The high-energy spallation neutrons produced at LANSCE would pass right through the biological bulk shield at a reactor, which is typically made of concrete containing a neutron-absorbing material such as boron. The LANSCE crypt is surrounded by a 3.7-meter-thick bulk shield containing a core of iron encircled by a layer of concrete. The bulk shield, in combination with the nickel reflectors within the crypt, reduces the radiation exposure of researchers to very low levels.

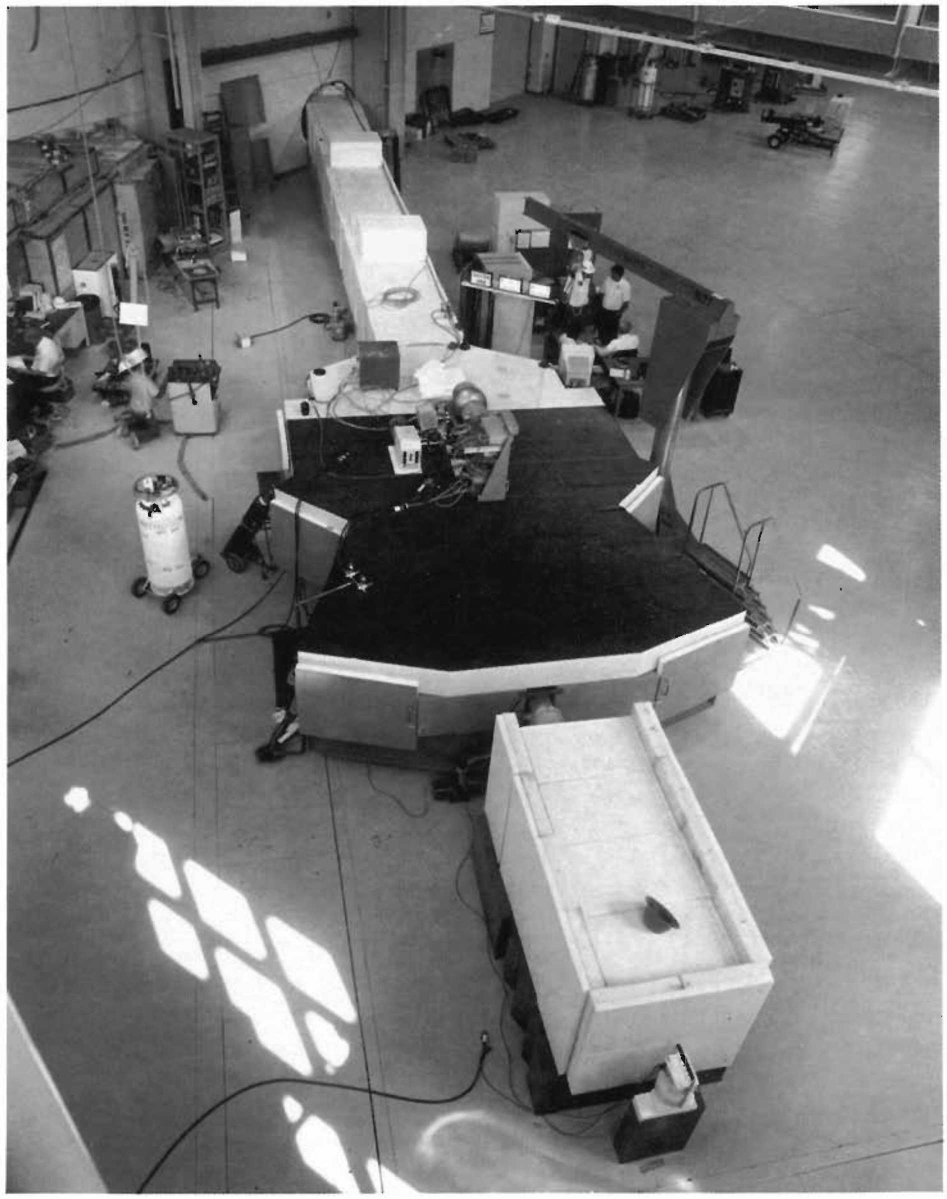
Neutron Spectrometers

All neutron-scattering instruments have certain common requirements.

Each needs a method for piping neutrons from the source to a sample and a system for detecting the neutrons that are scattered from the sample. The following sections describe some of the hardware used to achieve those ends.

Collimators. As Fig. 1 shows, neutrons leave the moderator surface in all directions. Only those traveling within a narrow cone of angles along a beam tube can reach a sample outside the bulk shield. To further decrease the size and angular divergence of the beam of neutrons exiting a beam tube, it can be fed through the bulk shield along a collimator. Jutting out from the walls of a typical collimator are boron carbide scrapers, which define a thermal neutron beam by absorbing those thermal neutrons that strike them. Boron carbide does not absorb neutrons with energies above a few keV; those neutrons are attenuated by the iron walls of the collimator. The very few neutrons with energies greater than 20 keV that escape the crypt form a beam somewhat larger than the thermal neutron beam—a halo. Because the halo would create undesirable background, it is absorbed by heavy shielding material outside the bulk shield. It is worth noting that a collimator is designed so that a straight line drawn between any point along its iron walls and the scattering sample passes through at least one of the boron carbide scrapers. Thus the pulse of neutrons incident on the sample is not broadened by thermal neutrons that leak through the collimator walls.

The cross-sectional area and shape of the neutron beam defined by a collimator are chosen to match the requirements of a neutron spectrometer. For example, the samples studied with the Single-Crystal Diffractometer are small. Consequently, the beam-defining apertures in its collimator are small. The reflectometer, on the other hand, uses two narrow beams whose shapes are dictated by the need to reflect them at very small angles from the flat surface of a sample.

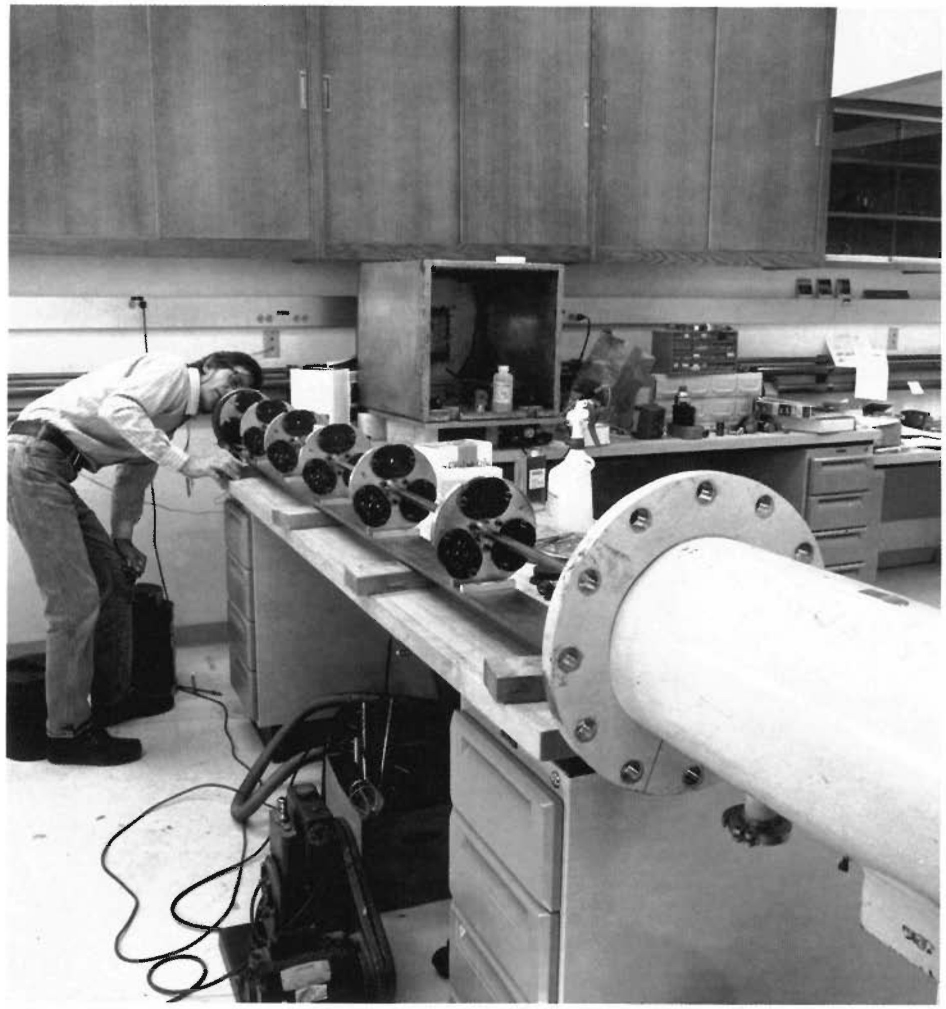


The Neutron Powder Diffractometer was the first instrument to be installed in the new addition to the experiment hall. The *d*-spacing resolution of this diffractometer is better than that of any other instrument of its type in the United States.

Many of the collimators within the LANSCE bulk shield can be flooded with mercury, which acts as a shutter, closing off the beam and allowing access to the sample. An interlock system ensures that no one has access to a spectrometer unless its shutter is closed. Thwarting of any one interlock prevents delivery of protons to the spallation target and thus in effect turns off all the beams.

Additional profiling of the neutron

beam takes place outside the bulk shield in each instrument according to individual design. For example, the Neutron Powder Diffractometer has five pairs of variable apertures in the incident beam line that allow the user to tailor the beam to the sample size. Neutrons that would miss the sample would produce unwanted background, so it is best to remove them from the beam by placing the apertures as far "up beam" of the sample and detectors as possible. Another instrument, the Low-Q Diffractometer, has a beam scraper that offers a single aperture or multiple apertures. The multiple apertures can be used to increase the neutron intensity when a weakly scattering sample is being studied. The sample must then be sufficiently large to intercept the multiple beams, which converge at the detector rather than at the sample.

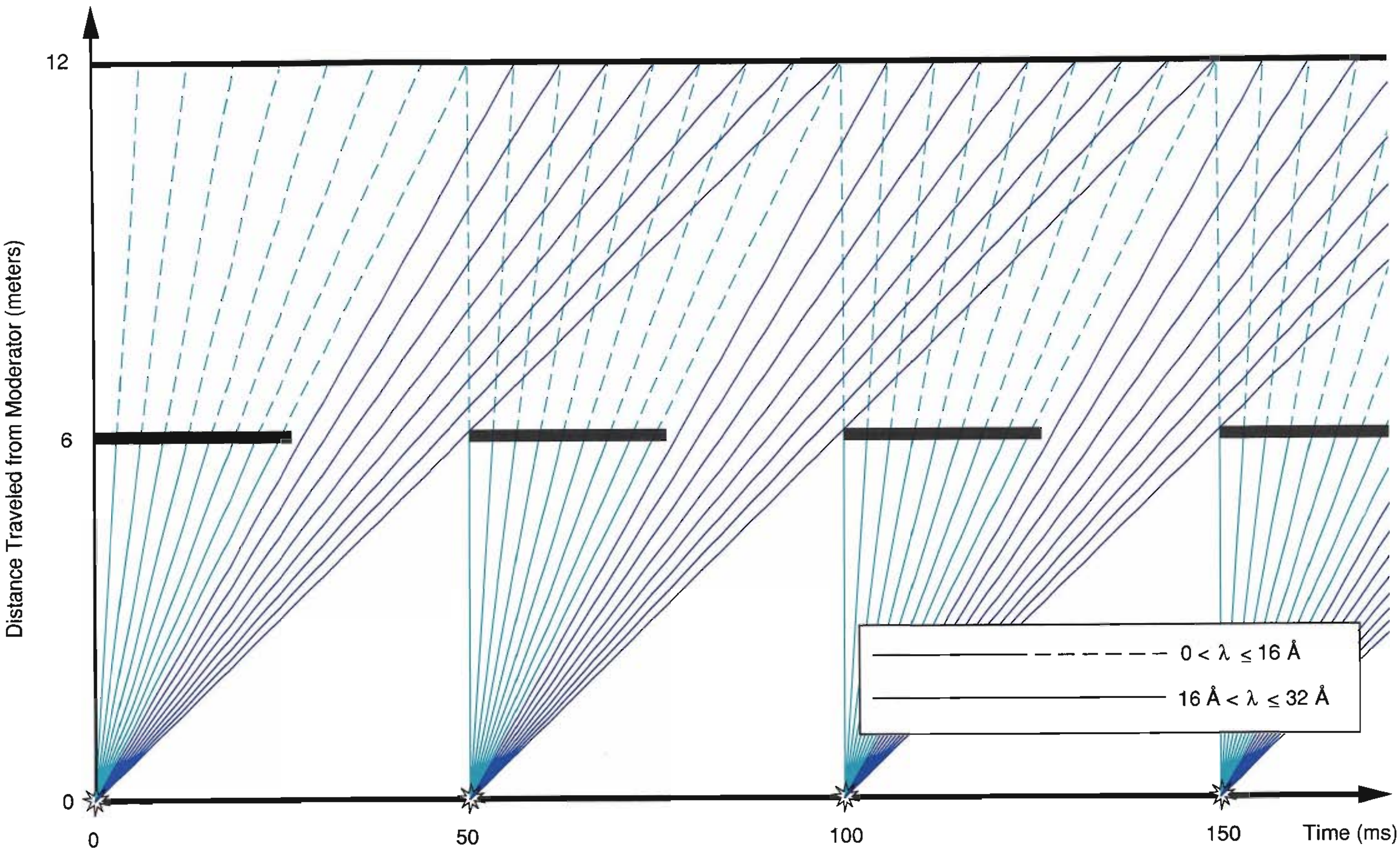


Rodney Hardee, instrument technician at LANSCE, peers along the beam path defined by the set of single holes in the top series of beam scrapers for the collimator of the Low-Q Diffractometer. (The series of beam scrapers at the 4 o'clock position also have single holes.) The series of beam scrapers at the 8 o'clock position illuminates the sample with a set of five beams rather than a single beam.

Guide Tubes. The astute reader may marvel at the inefficiency of the collimator shown in Fig. 1. Only those neutrons that leave the moderator headed almost directly for the spectrometer exit the collimator. Coaxing neutrons headed in the "wrong" directions into moving toward a spectrometer is not generally possible, but there is a trick we can play—we can install a neutron guide tube rather than a collimator. A guide tube is usually a rectangular-section tube of thick glass. The inner walls of the tube are highly polished and coated with a thin, smooth layer of nickel or, even better, isotopically pure ^{58}Ni. Neutrons that make a sufficiently small angle with a wall of the guide tube are totally reflected from the wall and therefore stay within the guide, headed toward a neutron spectometer. The "sufficiently small" angle, in degrees, is about one-tenth of the neutron wavelength in angstroms. For example, the critical angle for thermal neutrons with a typical wavelength of 2 angstroms is 0.2 degrees. The increased neutron intensity provided by a guide tube is worth its high cost, several thousand dollars per meter. The intensity gain is especially high for long-wavelength neutrons because their critical angles are greater.

Guide tubes are 10 to 100 meters long. They are evacuated to prevent neutrons from being scattered out of the tube by air. Guides have been used at reactors for some time—the first were in place at the Institut Laue Langevin in France in the early 1970s. The National Institute of Standards and Technology is currently installing guide tubes at its Washington, D.C. reactor, and a 25-meter guide will deliver ten times more 2-meV neutrons to the new LANSCE backscattering spectrometer than would a conventional collimator.

T-zero Choppers. Little can be done to change the fact that each pulse of



FRAME OVERLAP

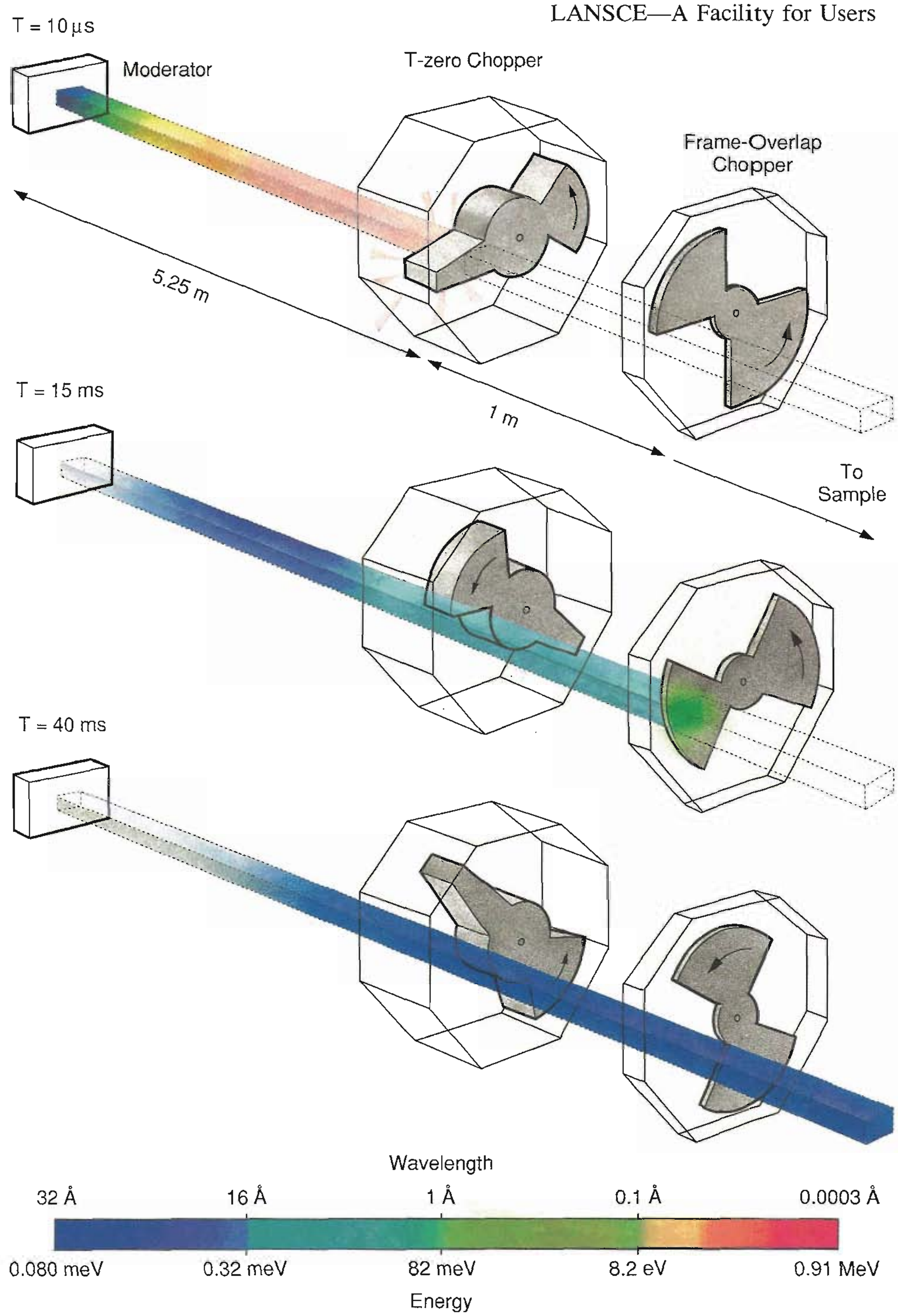
Fig. 3. The neutrons in each moderated pulse begin their flight to a detector at essentially the same time (within a small fraction of a millisecond). However, because they all have different energies, as time passes they spread out along the course, reaching the same distance from the moderator at different times after departure. That situation is depicted graphically here in plots of distance traveled versus time for neutrons with various energies. Each "explosion" on the time axis represents a pulse of neutrons emerging from a moderator. Note that fast neutrons from, say, the second pulse can reach a detector 12 meters distant at the same time as slow neutrons from the first pulse. To prevent such "frame overlap," which fouls up the time-of-flight measurements, a spectrometer can be equipped with a frame-overlap chopper (See Fig. 4). When the chopper is rotated at 10 times per second (half the repetition rate of the proton pulses) and at a certain phase relative to the proton pulses, it blocks neutrons with energies corresponding to wavelengths less than 16 angstroms. That mode of chopper operation is represented here by a thick horizontal line at a distance of 6.25 meters. Changing the phase of the chopper by 90 degrees (moving the thick horizontal line to the left or right a distance equal to its length) blocks neutrons with energies corresponding to wavelengths between 16 and 32 angstroms.

useful thermal neutrons emerging from a guide tube or collimator is preceded by a bright flash of high-energy neutrons and gamma rays generated when the proton pulse strikes the spallation target. One way of reducing the background caused by that radiation is to attenuate it with a T-zero chopper, a device so named because the zero of time for each neutron pulse is defined as the moment at which the proton pulse strikes the target. The high-energy neutrons and gamma rays travel so fast that they arrive at a spectrometer essentially at the same time as the proton pulse hits the target. A T-zero chopper, a 30- to 40-centimeter-thick slug of nickel alloy, rotates into the neutron beam in synchronization with the proton pulses and "chops" out both gamma rays and high-energy neutrons. Because the high-energy neutrons are scattered rather than absorbed, the chopper is placed inside a heavily shielded cave. The pulse of useful neutrons arrives at the chopper after the nickel slug has moved out of the beam path and passes out of the cave through a small window.

Frame-Overlap Choppers. Stripped now of background-creating high-energy neutrons, each pulse of neutrons flies on toward a sample and a detector. Initially tightly bunched, the neutrons gradually spread apart in space because their speeds differ. The spreading is depicted graphically in the distance-time diagram of Fig. 3. The "explosions" on the time axis represent neutron pulses leaving the moderator. Examination of Fig. 3 reveals that fast neutrons in one pulse will catch up with slower neutrons in the preceding pulse before the latter have reached a neutron detector, provided the flight distance is sufficiently great. This "frame overlap" clearly gets worse the longer the flight distance. The hare always catches the most motivated tortoise if the course they run is long enough! Because a neutron detector is sensitive only to the arrival of a neutron and not to its energy, frame overlap leads to assignment of erroneous times of flight (and hence energies) to neutrons with energies sufficiently different from the average. The frame-overlap problem is reduced significantly if the repetition rate of the neutron pulses is low, as can be seen by removing every other "explosion" on the time axis of Fig. 3. LANSCE thus has an advantage over other pulsed neutron sources because its repetition rate is lower (20 per second compared with 30 to 50 per second). However, even at a pulse repetition rate of 20 per second, a 12.5-meter flight distance leads to frame overlap if the bandwidth of the neutron wavelengths is greater than 16 angstroms.

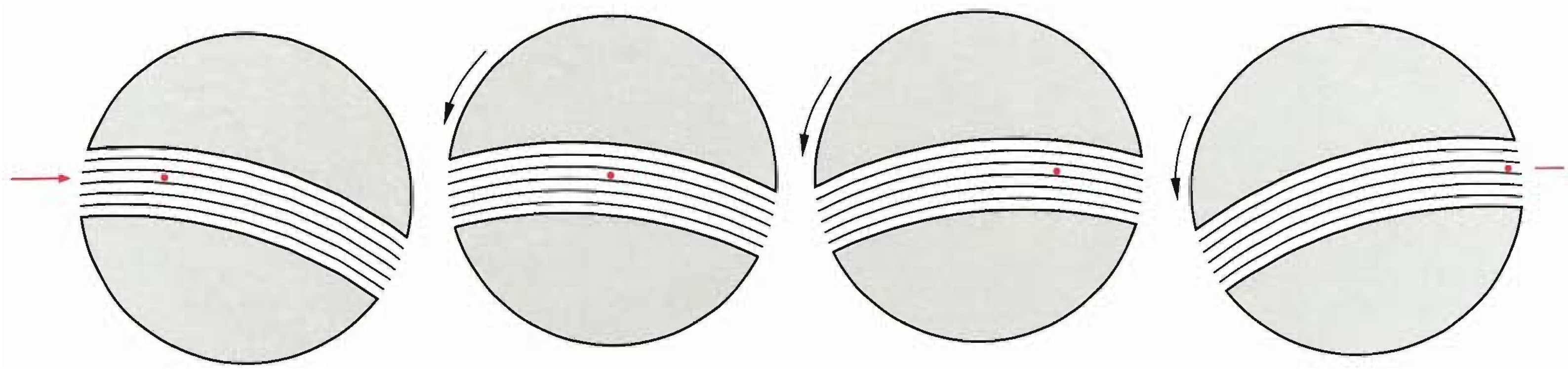
One way of avoiding frame overlap is to install a frame-overlap chopper, a device that closes for a prescribed amount of time during each pulse to prevent neutrons in a particular wavelength band from reaching the detector. The frame-overlap chopper on the reflectometer at LANSCE has a shape resembling that of a bow tie and is fabricated of a neutron-absorbing material. When the chopper is rotated at half the pulse repetition rate (10 times per second), its phase can be adjusted so that neutrons with wavelengths less than 16 angstroms are transmitted and neutrons with wavelengths between 16 and 32 angstroms are absorbed. Changing the phase of the chopper appropriately reverses the situation: Neutrons with wavelengths less than 16 angstroms are blocked, and neutrons with wavelengths between 16 and 32 angstroms are transmitted. Both wavelength bands can be used profitably on the reflectometer. The observant reader may have noticed that the chopper does not prevent frame overlap between fast neutrons in the $(n+2)$th pulse and very slow neutrons—those with wavelengths beyond 32 angstroms—in the nth pulse. Therefore, the very slow neutrons are reflected out of the beam by silicon wafers coated with nickel. Action of a T-zero chopper and a frame-overlap chopper is illustrated in Fig. 4.

Energy Selectors. Although the neutron pulses transmitted through a frame-



T-ZERO AND FRAME-OVERLAP CHOPPERS

Fig. 4. The LANSCE reflectometer has both a T-zero chopper and a frame-overlap chopper. The former scatters the burst of high-energy neutrons and gamma rays (red through yellow) that precedes the pulse of moderated neutrons; the latter absorbs lower-energy neutrons that would cause frame overlap as they spread out along the flight path because of their different energies (see Fig. 3). By t = 10 μs the T-zero chopper, which rotates 360° every 50 ms, has scattered neutrons with energies down to 1 MeV. By t = 15 ms the T-zero chopper has scattered neutrons down to 300 meV and rotated out of the beam. Energetic thermal neutrons (green and aqua) have reached and are being absorbed by the frame-overlap chopper, which rotates 180° every 50 ms. The remaining neutrons in the pulse have spread out along the flight path. By t = 40 ms the frame-overlap chopper has absorbed neutrons down to 0.3 meV (aqua) and rotated out of the beam, allowing very slow neutrons (blue) to proceed on to the sample. By changing the phase of the frame-overlap chopper, faster neutrons, rather than slower neutrons, can be allowed to reach the sample. Here pale color represents low beam intensity.



ENERGY-DEFINING CHOPPER

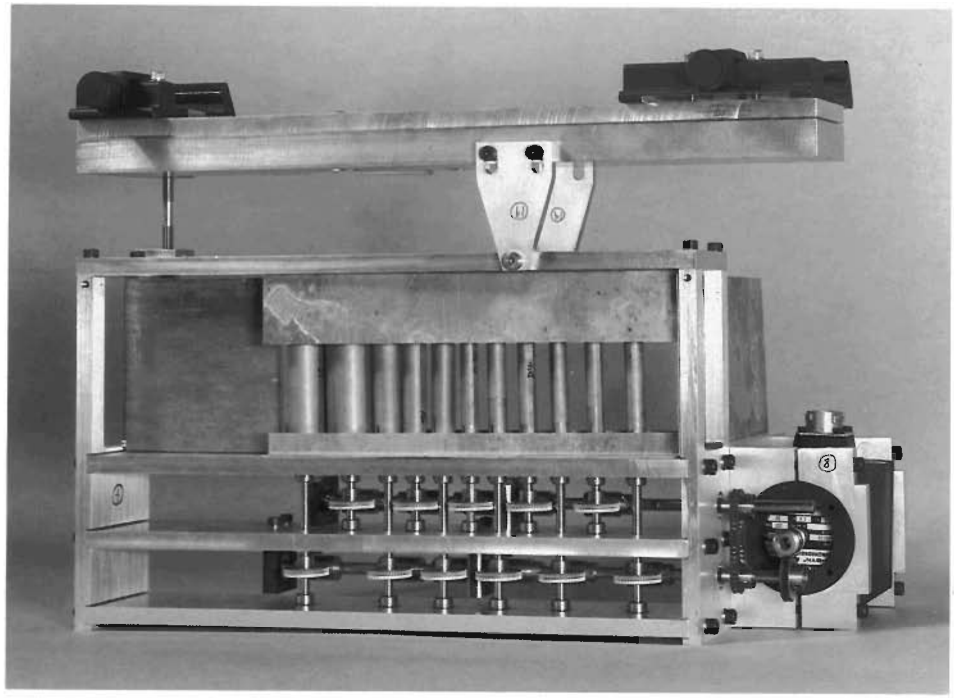
Fig. 5. A neutron (red point) traveling in the direction indicated by the red arrow can, if it has the proper speed, pass through the center of a curved slit in a rotating disk. Shown here are four snapshots of the neutron making its passage through one of several slits in an energy-defining chopper. (To an observer moving with the neutron, the slit appears to open up to allow passage.) Neutrons that do not have the proper speed strike the walls of the slit and are absorbed. A chopper of this type can be used to select a narrow band of neutron energies from either the incident or the scattered beam. Different neutron energies can be selected by changing the speed of rotation of the chopper.

overlap chopper have a reduced energy bandwidth, that bandwidth is still very broad. Such pulses can be used without further ado in elastic-scattering experiments because an elastically scattered neutron does not change energy during scattering and therefore its measured time of flight provides all the energy information required. In contrast, inelastic scattering experiments require knowledge of the energies of a detected neutron both before and after scattering. If the initial energy of an inelastically scattered neutron is known, say because only neutrons whose energies lie within a narrow band have been allowed (selected) to reach the sample, then its final energy can be calculated from its measured time of flight. Alternatively, if the final energy of an inelastically scattered neutron is known because only neutrons whose energies lie within a narrow band have been allowed to reach the detector, then its initial energy can be calculated from its measured time of flight.

Several methods are available for selecting, from either the incident or the scattered beam, neutrons whose energies lie within a narrow band. One method uses an energy-defining chopper, which can be thought of as a window that opens briefly to allow passage of neutrons with a particular speed. Such a "window" is usually achieved by rotating an assembly of curved slits in the beam line. The curvature of the slits and the speed at which the assembly rotates determine the energy of the neutrons that pass through the slits. Other neutrons strike the walls of the slits and are absorbed. The duration of the neutron pulse transmitted by the chopper varies with the width of the slits and the speed of rotation. Figure 5 illustrates the operating principle of such an energy selector, one of which is installed, close to the sample, in the incident beam line of Pharos, a new inelastic scattering instruments at LANSCE. (The instrument is named after the ancient lighthouse at Alexandria.) Magnetic bearings allow high-speed rotation (1200 times per second) of the chopper, and the chopper slit package is made from a strong composite material containing neutron-absorbing boron fibers.

One of the most common techniques for selecting a monochromatic beam of neutrons—at both accelerator and reactor sources—makes use of Bragg diffraction from a single crystal. The orientation of the crystal determines the energy of the neutrons diffracted toward a sample or a detector. When mounted in the scattered beam line, an energy selector of this type is called an analyzer. Each of the analyzers available for use with the LANSCE Constant-Q Spectrometer consists of an array of single crystals rather than one single crystal. All of the crystals have the same orientation, and their identical orientation is preserved when the crystals are rotated to allow diffraction from a different set of atomic planes (and hence detection of scattered neutrons with a different energy). (Realizing this feat with a single analyzer crystal is not possible because it would require a crystal of unattainable size.) Such an array can "analyze" the neutrons scattered by the sample through a wide range of angles. To increase the scattered-neutron intensity at the detector, dislocations have been introduced into each crystal by squeezing it in a special press. The squeezed crystal diffracts as if it were composed of many perfect crystal blocks ("mosaic blocks") that are slightly misoriented relative to one another. That is, it diffracts neutrons whose energies lie within a finitely (rather than infinitely) narrow band. Thus a greater number of neutrons are recorded by the detector. The increase in measured intensity is accompanied, however, by a decrease in energy resolution because the misoriented mosaic blocks diffract slightly different energies. Such compromises are not uncommon: Neutrons are scattered so weakly by matter that obtaining a measurable signal often requires being satisfied with decreased energy resolution.

Another method for selecting neutron whose energies lie within a narrow range makes use of polycrystalline "filters" that diffract neutrons with certain energies. The most commonly used filters are beryllium and beryllium oxide, cooled by liquid nitrogen, and pyrolytic graphite. The beryllium and beryllium oxide filters, used widely in connection with cold neutron beams, are almost transparent to neutrons with energies less than 5.2 meV and 3.7 meV, respectively, and strongly diffract neutrons with higher energies. Alternate detector elements of the LANSCE Filter-Difference Spectrometer are preceded by beryllium and beryllium oxide filters. Subtracting the signals in the two sets of detector elements yields the scattering law of the sample for neutrons whose final energies lie between 3.7 meV and 5.2 meV.



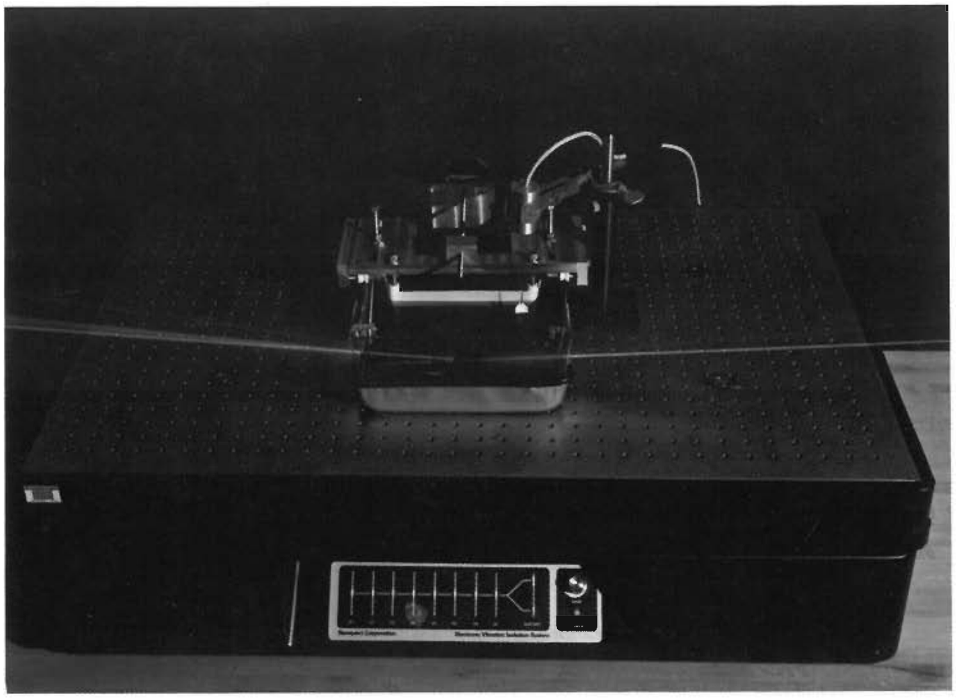
Each cylinder in this analyzer for the Constant-Q Spectrometer is a single crystal of germanium. All the crystals have the same orientation, and therefore the analyzer diffracts, toward an array of detector elements, neutrons that the sample has scattered through different angles but to the same energy. The diameters of the crystals vary because different thicknesses are required for optimum diffraction through different angles: Thicker crystals are required for smaller scattering angles. Note the mechanism for rotating the crystals in unison to orient other atomic planes perpendicularly to the plane of the analyzer. A similar analyzer containing single crystals of copper is available. It allows selection of a different set of energies and energy resolutions.

Sample-Environment Equipment. Most early neutron-scattering experiments were carried out on samples under ambient conditions. Because the questions being addressed by neutron scattering have become increasingly sophisticated, equipment for providing a wide range of sample environments has become increasingly prevalent. Temperatures down to 1.4 kelvins or up to a few hundred degrees Celsius are now considered routine and are available on almost all neutron spectrometers. Also readily available are cells in which single crystals or powders can be subjected to pressures up to a few tens of thousands of atmospheres. The pressure cells can often be mounted in cryostats and cooled to liquid-helium temperature. In addition, at some neutron-scattering centers high magnetic fields can be applied to samples.

Extreme sample environments are often easier to implement at an accelerator source than at a reactor source. Use of a white incident neutron beam implies that complete information can frequently be obtained by examining only those neutrons scattered through a narrow range of angles. For example, obtaining data that cover lattice spacings between 0.3 and 5 angstroms with the LANSCE Neutron Powder Diffractometer requires access to scattering angles between 78 and 102 degrees in the 90-degree detector bank, whereas obtaining data that cover lattice spacings between 1 and 5 angstroms with a reactor instrument fed 2-angstrom neutrons requires access to scattering angles between 23 and 160 degrees. Thus the paraphernalia required to subject a sample to extreme temperature or pressure need not, at a spallation source, be equipped with large neutron-transparent windows. Such windows are required at a reactor source and are not always easy to implement because few structural materials are transparent to neutrons (aluminum is one of the best).

Some types of sample-environment equipment are specific to particular types of spectrometers. For example, an active vibration-isolation system is installed on the LANSCE reflectometer. It serves to eliminate ripples on the surface of a liquid from which neutrons are being reflected. The liquid is usually contained in a Langmuir trough, which is rather like a Teflon-coated baking pan. The pan is equipped with a lid to maintain constant vapor pressure above the liquid and a boom to allow compression of monolayer films on the liquid surface.

A special apparatus that may be found on instruments designed to provide small-angle-scattering data is a Couette, or shear, cell—a device in which a fluid can be subjected to shear by being confined within the gap between two coaxial cylinders rotating at different speeds. Analysis of small-angle-scattering data for the fluid yields information about shear-induced structural changes. The shear cell that will soon be installed on the LANSCE Low-Q Diffractometer is made of fused silica, a material that adds little background to the small-angle-scattering signal. At a maximum torque of 5 newton-meters, a shearing rate of 10,000 per second will be achieved when the gap between the cylinders is 0.3 millimeter.



A Langmuir trough is used to contain a liquid whose surface is being studied by neutron reflectrometry. The vibration-isolation system on which the trough sits eliminates ripples on the surface. Laser beams are used to simulate the neutron beams during alignment of the sample.

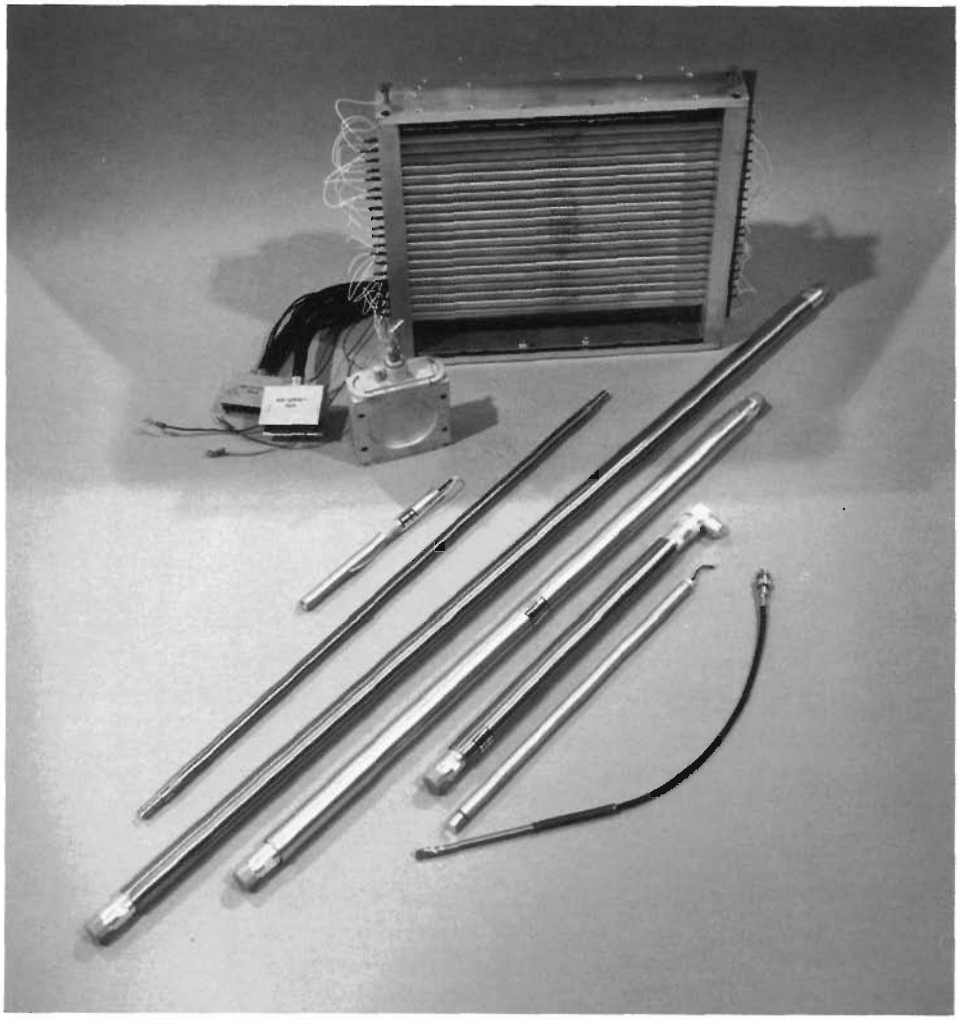
Detectors. Almost all neutron detectors are so-called gas detectors containing ^{3}He, one of the few isotopes that have a high cross section for absorbing neutrons. When a ^{3}He nucleus absorbs a neutron, a proton and a triton are formed. Both have considerable energy and are thus capable of knocking electrons out of nearby ^{3}He atoms. The electrical pulse that occurs as the electrons migrate to an anode maintained at a high voltage is detected by an electronic circuit. The neutron is then said to have been counted (or recorded or detected). The ^{3}He gas is generally contained within a thin-walled, small-diameter tube of aluminum or stainless steel. A wire strung along the tube axis serves as the anode; the tube wall serves as the cathode. The efficiency of a neutron detector (the fraction of the neutrons entering the detector that are counted) increases with the number of ^{3}He atoms in the tube, that is, with the product of gas pressure and tube volume. In addition, because the cross section of ^{3}He for absorbing neutrons increases with decreasing neutron energy, so also does the detector efficiency. Typical efficiencies are not far from unity.

Each time a proton pulse is fired at the LANSCE spallation target, an electronic clock is started. The clock is read when the electrical pulse created by absorption of a neutron is detected and that time is recorded by the data-acquisition system as the measured time of flight of the neutron. Because the electrical pulse occurs at some time after the neutron arrives at the detector, the measured time of flight is longer than the true time of flight. However, the delay between the neutron's arrival and detection of the electrical pulse is about a microsecond, whereas the true time of flight of the neutron is on the order of several milliseconds. Therefore, the delay introduces a negligible error in the measured time of flight.

The simplest neutron detectors do not provide information about where a neutron is absorbed. More sophisticated detectors, called linear-position-sensitive detectors, do provide such information in one dimension, namely the axial dimension. Therefore a single linear-position-sensitive detector can be used to count neutrons scattered through different angles. Position sensitivity can be extended to two dimensions by using a hollow disk to contain the ^{3}He instead of a tube. A grid of anode wires strung across a circular cross section of the disk provides the two-dimensional position information.

Many of the neutron detectors used at LANSCE are of the simplest type. Their size varies between 5 mm in diameter by 150-mm long to 25 mm in diameter by 1 meter long. Linear-position-sensitive detectors varying in length from 200 mm to almost 1 meter are installed on several LANSCE spectrometers. The accuracy with which those detectors can determine the position at which the neutron was detected varies between 1.8 mm and about 5 mm. Two LANSCE diffractometers are equipped with a two-dimensional position-sensitive detector. The one on the Single-Crystal Diffractometer covers a square area 25 centimeters on a side, whereas the one on the Low-Q Diffractometer covers a circular area more than four times as large—and is considerably more expensive!

Each instrument has a special gas detector called a beam monitor, which contains a low density of ^{10}B nuclei (as BF_3) and detects only about one neutron out of every hundred thousand. The beam monitor provides the energy spectrum of the neutrons incident on a sample. That information is used when the neutron scattering law for the sample is calculated from the data provided by the detectors in the scattered beam.



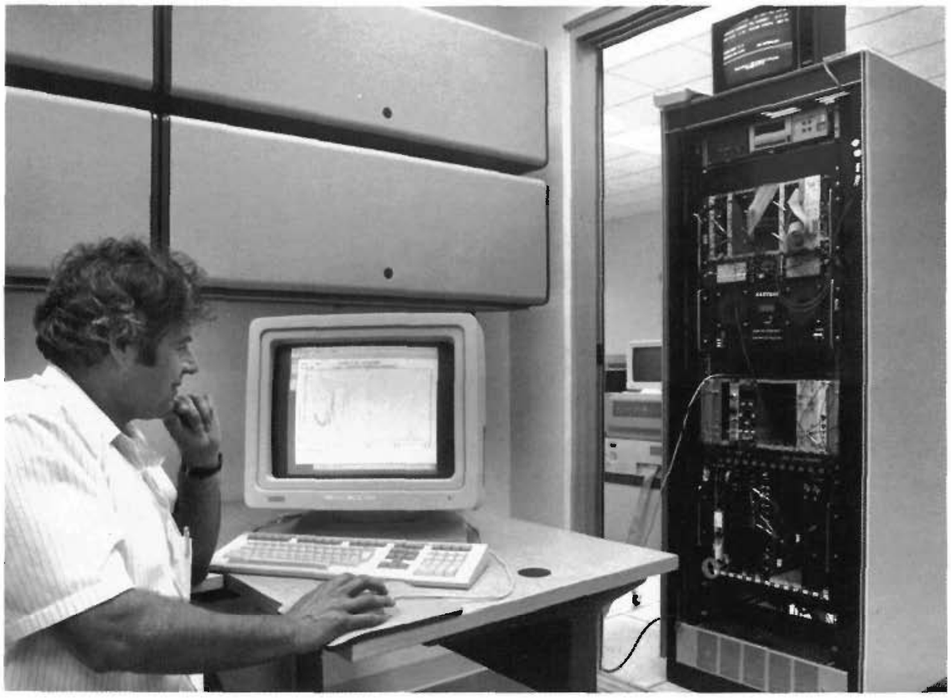
This display of gas detectors used at LANSCE includes, from bottom right, a 6-mm by 100-mm detector from the 5-degree bank of the High-Intensity Powder Diffractometer; a 12-mm by 300-mm detector from the Neutron Powder Diffractometer; a 25-mm by 300-mm detector; a 25-mm by 600-mm detector; a 25-mm by 1-meter detector from Pharos; a 12-mm by 600-mm linear-position-sensitive detector; a 12-mm by 150-mm detector from the Constant-Q Spectrometer; a beam monitor; and the array of 12-mm by 300-mm linear-position-sensitive detectors from the Surface Profile Analysis Reflectometer.

Data-Acquisition and -Analysis Systems. Electronic signals from the neutron detectors on each LANSCE spectrometer are fed into a data-acquisition system solely dedicated to that spectrometer. Because most of the spectrometers are equipped with a detector system containing more than one detector element, the number of neutrons recorded per second can be very large—up to 100,000 on the High-Intensity Powder Diffractometer, for example. The LANSCE data-acquisition systems are designed to handle such a barrage of information, storing both the time of flight and detector element (scattering angle) corresponding to each detected neutron. Each data-acquisition system is based on an electronic transmission line called a FASTBUS. Along this computer "highway" thirty-two "lanes" of signals are directed according to internationally standard protocols. A FASTBUS is capable of handling 2,000,000 events per second.

Data from each LANSCE instrument are delivered to a VAX-station computer with 9 megabytes of memory; data files are written on a local magnetic 300-megabyte disk. Data are then archived on a 150-gigabyte optical disk. (Such a disk could store the entire contents of *Encyclopaedia Britannica* 600 times).

Thirty data-analysis systems are available, each based on a VAX 3100 workstation and providing color graphics and dial-in capabilities.

The veritable deluge of data that pours out of a spectrometer at a spallation source can be an advantage for survey experiments. On the other hand, knowing what measurements to make next is very difficult when the full import of data already obtained has not yet been comprehended. Therefore, high-speed computers are needed to convert raw data into neutron scattering laws, as are advanced computer graphics and image-processing software to provide insightful views of data and results of calculations.



Walter Kalceff, a user from the Department of Applied Physics, University of Technology, Sydney, Australia, uses the data-acquisition system for the High-Intensity Powder Diffractometer to check on the progress of an experiment.

The LANSCE User Program

Because neutrons are much in demand and available only at a few specialized facilities, the experimenter who needs neutrons is forever chasing after them. He or she often applies well in advance to more than one facility to ensure getting some precious beam time on an instrument. Beam time is of course available at LANSCE only when LAMPF is up and running, and its running period is limited by funding constraints to about five or six months a year. LANSCE issues a call for proposals before each scheduled running period. In response, scientists from universities, industry, and other research facilities around the world submit their proposals, which are examined by an external program advisory committee LANSCE shares with the Intense Pulsed Neutron Source at Argonne National Laboratory. An internal program advisory committee also exists; it considers beam-time allocation for work of programmatic interest to the Laboratory.

Oversubscription for instrument beam time by a factor of 2—even more on the Low-Q Diffractometer and the High-Intensity Powder Diffractometer—has been the norm during the three years the LANSCE user program has been in effect. There is no charge to researchers for nonproprietary experiments, but DOE cost-recovery rules apply to experiments not publishable in the open literature.

LANSCE operates around the clock during the run cycles. Giving users directions to the facility is quite easy. One just says, "... and from the entrance gate of TA-53, just continue on down La Mesita Road for about a mile until you see a pink building on your right."

"'Pink?" questions the user.

"Yes, you won't be able to miss it—even at night."

And when they arrive, they note that the desks inside aren't made of gray metal and the kitchen has hot-pink counters. More important, they note that the new 18,000 square-foot experiment hall and the well-equipped data rooms are part of a facility that gives them a higher peak neutron flux on their sample than any other spallation source in the world.

LANSCE has seven working neutron spectrometers; two more are under construction. Because an experiment team often includes two or three people, a visitor count between ten and twenty at any one time during the run cycles is not unusual. Most experiments take between two and ten days to complete; powder-diffraction and small-angle-scattering experiments are relatively quick, whereas inelastic-scattering experiments may take a few weeks. Each user is assigned a local contact—one of the LANSCE scientific staff—who assists in setting up the user's experiment and explains the subtleties of the data-acquisition system. Arrangements can be made for the user who wishes to stay on at LANSCE for a few days after the experiment to complete an analysis, or at least to get the data into a form more convenient for analysis back home. In most cases, the working relationship between visitors and LANSCE scientists quickly develops into a true collaboration, one in which ideas and knowledge are freely exchanged.

LANSCE provides the target assembly, the data-acquisition and -analysis systems, the neutron-scattering instruments, and the required support services. The Medium Energy Physics Division operates the PSR that delivers proton pulses to LANSCE and the WNR facility. Support for LANSCE and PSR is given by the Office of Basic Energy Sciences of the DOE and by the Laboratory. Operation of the LAMPF accelerator itself is handled by the Medium Energy Physics Division with support from the DOE-OER Office of High Energy and Nuclear Physics.

In July 1989 the Laboratory's neutron-scattering center was officially dedicated in honor of former New Mexico Congressman Manuel Lujan, Jr. When now Secretary of Interior Lujan arrived at LANSCE for the dedication ceremonies, he noticed pictures of the early days of Los Alamos hanging on the wall. Secretary Lujan went straight to the picture of the post exchange and said he worked there making sodas during the war. It seems appropriate that a research center at Los Alamos should be named for a native son of San Ildefonso and long-term member of the House Committee on Science, Space, and Technology.

Conclusion

LANSCE has demonstrated the unique capabilities of a high-intensity pulsed neutron source and has furthered the development and refinement of neutron-scattering instrumentation. It is truly an outstanding tool for research in many areas of condensed-matter science. In addition, LANSCE plays an important role in the technological advancements of our society and provides a unique educational opportunity for graduate students in a wide range of disciplines. ■

Acknowledgments

The authors wish to thank the staff at LANSCE who built the instrumentation described in this article.

Further Reading

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Dianne K. Hyer received her Bachelor's degree from Louisiana State University and Master's degree from the University of New Mexico. She holds a lifetime teaching credential from the state of California and professional teaching credentials in both elementary and secondary education from the state of New Mexico. She was the first Computer Coordinator for the Los Alamos School District and has taught in both the mathematics and the computer science departments at the University of New Mexico, Los Alamos. Dianne joined the Laboratory in 1985 as a staff member in the Physics Division's inertial confinement fusion program. She moved to LANSCE in 1987 and, as science coordinator, organized its user program. Dianne is currently co-author and Project Director of the Los Alamos SWOOPE Project—an innovative environmental science program in which scientists, teachers, and students collaborate in gathering environmental data of national concern. Dianne enjoys music, philosophy, contemplating the universe, her children, being in the middle of ideas that grow, producing musicals, and catamaran racing.

The biography of co-author Roger Pynn appears on page 31.