First Neutrons from Rutherford Lab's SNS

Although it will take 2 years of commissioning to reach full intensity, the Spallation Neutron Source will be the world's most powerful

Chilton, United Kingdom. Researchers at the Rutherford Appleton Laboratory here are still savoring a recent triumph. With everything working perfectly from the start, on 16 December the researchers irradiated their first samples with neutrons from the Spallation Neutron Source (SNS), which will soon be the provider of the world's most intense pulses of neutrons for structural and spectroscopic investigations of materials by means of neutron scattering.

The sweet taste of success was all the more so because neutron scatterers visiting Rutherford last year during the final phases of construction had none too diplomatically managed to convey their skepticism that the SNS project, already delayed more than 2 years by budgetary problems, would meet its goal of becoming operational during 1984.

However, following a successful initial attempt in September at extracting pulses of protons from a new synchrotron—the heart of the SNS—the researchers worked feverishly at laying and aligning a 150-meter-long beam transport line with 65 large magnets to focus the particles and guide them toward a uranium target, the source of the intense pulses of slow neutrons. And, as project head David Gray proudly reported in January to colleagues from around the world at an international conference on neutron scattering at the Jülich Nuclear Research Center in West Germany, neutrons streamed forth on the first try and ahead of the deadline.

Obtaining the neutrons, while of undoubted symbolic value, actually represents only the first stage of a quite lengthy SNS commissioning process. Following the current shutdown to allow for the completion of the complex target assembly, which bears some resemblance to the core of a reactor, and other touches left unfinished in the rush to get at least a weak neutron beam out by the end of the year, Gray and his Rutherford co-workers are to commence this spring the task of gradually raising the intensity to the full design value by the end of 1986. Neutron scattering experiments with the six instruments already in place are scheduled to begin at the same time.

Even before achieving full intensity, the SNS will become the world's leading source of pulsed neutrons. Sources for neutron scattering come in two types, steady state and pulsed. The French-German-British Institut Laue-Langevin (ILL) at Grenoble, which uses a reactor to provide a high flux of steady-state neutrons, is considered the pacesetter in its category. Although continuing lean research budgets in the United Kingdom may hamper the full exploitation of the SNS, from the point of view of neutron scatterers in the United States, keeping up with the Europeans in this important field will be more difficult than ever. "They're going to blow us out of the water. . . . It's a heck of a machine," was the way one green-eyed American put it.

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Once an esoteric technique that developed in the 1950's with the use of low-flux research reactors for crystallography and investigating magnetism in materials, neutron scattering has progressively been embraced by solid-state physicists, materials scientists, chemists, polymer scientists, and biologists. Applications span the range from the most basic to the most applied research, while high-power research reactors specially designed to maximize the neutron flux began to be available in the mid-1960's and some now provide intensities more than 100 times that available early on.

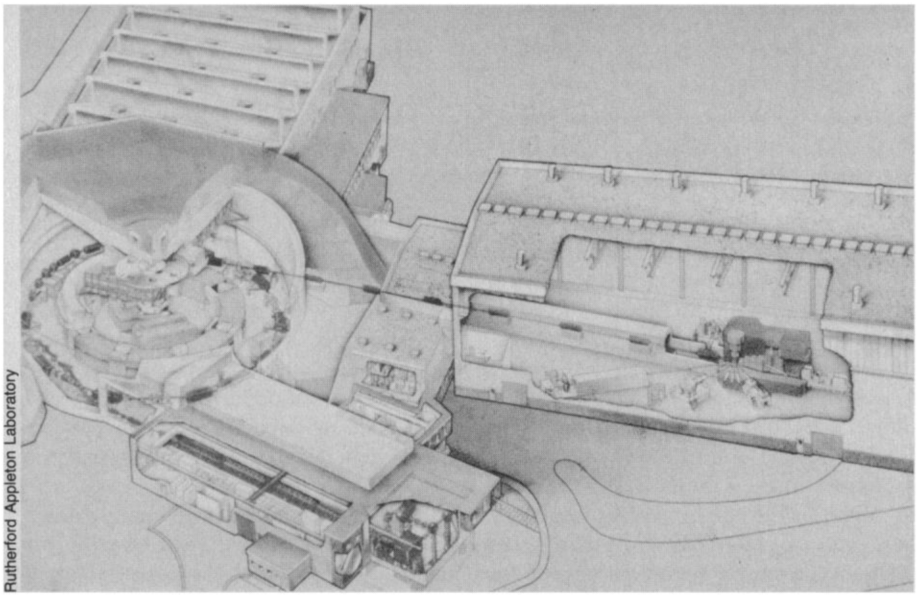
One contribution made by researchers using neutron scattering on the basic side is recalled by Martin Blume, Deputy Director of Brookhaven National Laboratory, which has a reactor of power comparable to the ILL's and an unfunded proposal for more extensive development and instrumentation. Neutron scattering has provided much of the detailed data concerning phase transitions in solid systems, critical phenomena in magnetic materials, in particular. Learning how to treat many-particle systems that act cooperatively as in phase transitions was one of the tasks that helped transform solid-state physics theory to a sophisticated discipline whose ideas have spread and been widely adopted, even by elementary particle theorists.

On the opposite extreme, consider the experience of the Atomic Energy Research Establishment, Harwell, which lies adjacent to Rutherford and has two medium-sized research reactors. Harwell obtains only half its funding from the U.K. Atomic Energy Authority and has to sell its expertise to other government agencies and to private industry to get the rest.

Peter Schofield, neutron beam manager at Harwell, shows a visitor real-time neutron radiography "movies" demonstrating the effect of temperature on the oil flow within a client's internal combustion engine, a feat made possible by the ability of neutrons to penetrate deeply into metals while simultaneously being strongly scattered by the hydrogen in hydrocarbons. And with neutron diffraction and small angle scattering, respectively, it is possible to map out without cutting the specimens open such characteristics as the strength of residual stress fields around welds, which affects their susceptibility to failure, and the size distribution of second phase precipitate particles, which affects the brittleness of steel alloys.

Although neutron scattering has grown up with reactors as sources, the future may belong increasingly to accelerator-based facilities as the reactors wear out after a lifetime of 25 years or so. The shift is partly due to an extended lull in the advancement of reactor technology, so that there is no immediate prospect for a significant increase in the obtainable neutron intensity, which neutron scatterers badly need for the kinds of experiments they want to do. Removal of heat from the very small cores of reactors designed for maximum neutron production is the limiting and unsolved consideration.

Accelerators, which generate pulses of neutrons, provide an alternative to reactors and have the potential for higher intensities. A beam of protons of energy 500 million electron volts (MeV) or more strikes a target made of uranium or another heavy element, thereby chipping away neutrons from the target nuclei and giving rise to the term spallation source. Although the spallation process does generate less heat than fission, the pulsed operation is the key to higher neutron intensites because heat can be removed between the pulses.



Rutherford Appleton Laboratory

SNS layout

Negative hydrogen ions are injected into the synchrotron at the left from a 70-MeV linear accelerator, and the 800-MeV extracted proton beam is transported to a target station in the large experimental hall on the right.

As in a reactor, the neutrons are initially very energetic but can be slowed down by collisions with the nuclei in a moderator material, such as water. The temperature of the moderator determines the range of kinetic energies and hence velocities of the emerging neutrons. One of the features that has made the ILL so successful was the early provision of a moderator cooled to cryogenic temperatures (cold source). The very slow or long wavelength neutrons from cold sources have made it possible to improve the resolution of structural and spectroscopic studies, especially of such large and complicated systems as polymers and biological macromolecules.

However, the difference between the energy spectra of the neutrons from spallation sources and reactors means that, after being moderated, the neutrons from the former are weighted toward higher energies. Thus, a room-temperature moderator in a spallation source will generate large fluxes of neutrons with energies of about 1 electron volt, whereas those from a reactor decrease rapidly above 0.1 electron volt.

Comparison of the intensities of steady-state and pulsed sources by their respective adherents generates almost as much heat as fission itself partly because it is difficult to weigh directly the merits of high time average versus high instantaneous or peak intensities. At the moment the technology for high-current proton accelerators is not fully mature, so that the time average neutron intensity delivered to experiments by the SNS will be considerably below that from the ILL, while the peak intensity will be much greater. Moreover, the difference between the energy spectra further complicates discussions about the merits of reactors and spallation sources. Alan Leadbetter, who is in charge of the SNS scientific program, raised a few eyebrows at the Jülich meeting with his estimate that the SNS would be superior to the ILL for neutrons of energy greater than about 0.01 electron volt, depending on the experiment.

Rutherford's entry into spallation neutron sources was by way of its accelerator expertise. In the early 1970's, the lab was still primarily a high energy physics facility and had a 7-billion-electron-volt (GeV) proton synchrotron called NIMROD. Laboratory scientists had just gotten approval to build a new 70-MeV proton linear accelerator to replace the original device that injected particles into NIMROD and thereby increase its intensity by a factor of 5, recalls Gray.

But Britain was having trouble financing its high energy physics program, which included a substantial subscription to the European Laboratory for Particle Physics (CERN) and the upkeep of its own accelerators: NIMROD and a 5-GeV electron synchrotron at the Daresbury Laboratory. The Science and Engineering Research Council (SERC) decided in 1972 to concentrate on CERN and phase out the accelerators at home. NIMROD's last run ended in 1978.

Despite the emphasis on high energy physics, Rutherford had a small neutron scattering group to support British university scientists using the reactors at Harwell or working at the ILL. According to Harold Wroe, who headed the group, one of its jobs was to look into the question of what kind of source might come after the ILL reactor, which went critical in 1971. The group quickly concluded that, for the reasons already mentioned, a better reactor was unlikely, so it shifted its attention to spallation sources, building on work at Argonne National Laboratory. The Intense Pulsed Neutron Source, which started up 3½ years ago at Argonne (*Science*, 4 September 1981, p. 1097) and generates the highest pulsed neutron intensities anywhere at the moment, is the current U.S. result of that early work.

During this same period, an already strong community of British neutron scatterers grew even more numerous as researchers started flocking to the ILL. Therefore, following a futile attempt by Rutherford to stay in the higher energy physics game (a plan for an international electron accelerator project was doomed by a German decision to construct a similar machine at the DESY laboratory in Hamburg), all the ingredients were there for a proposal to build a world class pulsed neutron source: unused accelerator expertise and equipment at a national laboratory and a vocal group of potential users.

A formal proposal did in fact materialize rather quickly. Submitted in October 1976, it was approved only 6 months later. No doubt a major ingredient in making the project palatable was cost. By using the accelerator and experimental halls that housed NIMROD and by making extensive use of NIMROD components, Rutherford was able to propose a facility priced at only half that of an all-new one. Though inflation has raised the original cost estimates, Rutherford spent about £50 million on the SNS, while the estimated replacement value of the reused structures and components is about the same.

Neutron scattering is not the only direction in which Rutherford has broadened its interests. With the resettlement of the Appleton Laboratory on the Rutherford site in 1979 and the consequent establishment of the Rutherford Appleton Laboratory, the lab acquired a substantial interest in space science and astronomy. The announcement that the SNS would go ahead was made at Rutherford on the occasion of the inauguration of its Central Laser Facility. And there is a growing microelectronics- and computer-related activity.

In the original plan, the SNS construction was to end in 1982, following which the commissioning phase was to begin. But the long-running financial problems of British science that were partly responsible for Rutherford's originating the project in the first place intervened to threaten its completion and in the end stretched it out considerably. Large construction projects naturally have a funding profile that is strongly peaked, but the SERC was forced in 1980 to adopt a level profile with equal amounts being spent each year, leading to a first half of 1984 completion.

Even with this sacrifice, the financial pressure has been continuous. Though some might argue that the SNS has not shared as fully as others in the belt-tightening required by the times, the project just barely made a more recent end-of-1984 deadline and the number of neutron scattering instruments ready to go is only six, as compared to the full potential of more than 20. At this late date, it is still not known for sure how much money will be available to operate the SNS this year.

Operating time is a crucial factor because Rutherford scientists are entering a new regime in proton synchrotron operation in order to obtain the high beam currents required if the SNS is to reach its design specifications. The SNS synchrotron is to have a time-average current of 200 microamperes, which is quite large for proton machines. The synchrotron in Argonne's pulsed source accelerates a current of 12 micromamperes, by comparison.

The principal difficulty is that the high-energy protons, which are injected at 70 MeV (from the linear accelerator originally designed for NIMROD but never commissioned) and accelerated to 800 MeV, can induce considerable radioactivity, overheating and subsequent crack formation due to thermal stress, and microscopic radiation damage in the synchrotron structure whenever the beam goes astray, which it will until Rutherford accelerator scientists master their machine.

To minimize these dangers, the plan is initially to operate the synchrotron with only 20 microamperes beam current. The current will then be gradually increased over the commissioning period. The goal is never to lose more than 2 microamperes of current, as the radioactivity induced by this amount can be handled by what Gray calls "conventional techniques"; that is, remote handling is not required. At the design current of 200 microamperes, this represents a beam loss of only 1 percent.

One side of the high current is a large concentration of closely packed protons, which because of their mutually repulsive positive charges would rather not be so intimate with one another. Keeping the pulse short requires a high power in the radio-frequency cavities that feed energy into the beam. As the pulse circulates around the 160-meter circumference synchrotron ring at the rate of about 2 million times per second, its appreciable space charge induces voltages in the surrounding structures. Induced voltages in the radio-frequency cavities have to be compensated for by the power supplies that drive the cavities. However, the space charge can also cause various instabilities that blow up the beam until operators learn how to avoid them. For example, the voltage induced as the leading edge of a pulse passes can feed back to the trailing edge, the so-called head-tail instability.

All the ingredients were there for a proposal to build a world class pulsed neutron source.

The other side of the high current is the pulse repetition rate. As each pulse is accelerated, the fields in the bending and focusing magnets must increase in step in order to maintain a constant orbit. The cycling of the magnetic fields at a rate of 50 times per second generates eddy currents in electrically conducting structures that then distort the fields. The SNS designers dealt with this problem by replacing the usual stainless steel beam pipe with ceramic, at least inside the magnets, which necessitated some creative engineering techniques to make 5-meter-long, vacuum-tight ceramic sections.

After reaching an energy of 800 MeV (for the moment it is only 550 MeV, as only four of the six planned radio-frequency cavities have yet been installed, partly for financial reasons and partly to get neutrons out as early as possible), the proton pulse of 0.4 microsecond duration is kicked out of the synchrotron by a special magnet and sent on its way down the transfer line to the uranium target. The target comprises 34 kilograms of depleted uranium (99.8 percent uranium-238) in the shape of a horizontal stack of 23 increasingly thick plates clad with a zirconium alloy (zircalloy). The heat due to the spallation process that generates about 25 neutrons for each bombarding proton or a total of 6.5×10^{14} neutrons per pulse is removed by circulating heavy water.

Four moderators sit above and below the target assembly. Above are two ambient temperature water moderators, while below are two cold sources (liquid methane at 90 K and liquid hydrogen at 25 K). Heavy water–cooled beryllium structures function as a reflector. Target, moderators, and reflector are supported inside a helium-filled stainless steel vessel 3 meters in diameter, which in turn rests inside a 5-meter-thick biological shield of steel and concrete.

Piercing the shield are 18 ports for neutrons, although only 10 of these are now fitted with neutron collimators or guide tubes. Nine of these lead to the six operational instruments and to three instrument development projects. There is space for up to 25 instruments eventually, and there is also a vacant NIMROD experimental hall, which could some day be the site of a second target station providing an even higher neutron flux and an accompanying experimental area. Rutherford scientist Alan Carne and his co-workers have been collaborating with researchers from Jülich on ways to increase the neutron output by up to a factor of 10.

One method under investigation is a target consisting of a heavy metal core within a blanket of fissile material (a subcritical multiplying or fissioning target), and this might go in the vacant hall. A nearer term solution, for which plans are already well developed for the Argonne pulsed source, is the addition of enriched uranium to the present target assembly, a booster target in the jargon.

The pulsed nature of spallation sources has important consequences for the way experiments are done; it dictates the use of time-of-flight techniques. For example, in diffraction experiments neutrons having a range of wavelengths irradiate the sample simultaneously, while the wavelengths of the neutrons reaching the detector are determined from the time it takes them to arrive.

Neutron scattering experiments involve the measurement of changes in the energy and momentum of neutrons as they pass through a sample. Experiments fall generally into two classes: elastic and inelastic scattering. Elastic scattering, which includes diffraction, involves no transfer of energy from the neutrons to the sample. The momentum transfer is directly related to the angle through which neutrons are scattered and is used to gain structural information.

Inelastic scattering, as the name implies, results when there is an energy transfer due to such processes as excitation of lattice vibrations and is therefore a spectroscopic technique. There is some flexibility in independently varying energy and momentum transfer, which is one feature that gives scattering (whether neutrons or x-rays) a leg up over the traditional optical absorption or related techniques in mapping out dispersion curves and other excitation spectra, the ultimate aim of much of solid-state spectroscopy. The neutron's magnetic moment gives it the further ability to investigate the magnetic structure of materials.

With only six instruments at the start, the SNS will not be in a position to blanket the field. The ILL, by comparison, has 33 instruments and will soon be adding more. Of the six SNS instruments, whose average cost is about £600,000 each, three are elastic scattering instruments (diffractometers), two are inelastic spectrometers, and one is a quasi-elastic spectrometer. Quasi-elastic processes are low-energy dynamic effects such as molecular diffusion and rotation that have the effect of adding broad but lower intensity shoulders to the sharp peaks due to elastic scattering. Each instrument looks at a specific moderator, but the design of the shielding is such that any port can be arranged to look at any moderator. Moreover, the moderators can be tailored to provide neutrons optimized for different applications.

The prospects for additional instruments are mixed. Funding has been available for development work on three new instruments, which will be available for experiments when the techniques are worked out. But money to convert these into fully engineered instruments for university researchers, who will be the main class of SNS users, is lacking. The SERC has let it be known that spending on neutron scattering (mainly divided between the ILL and the SNS) will be reduced. The hope is that contributions from outside the United Kingdom in the form of instrument development and construction will take up some of the slack. In fact, one of the six instruments already in place, the high-resolution quasi-elastic spectrometer, actually comes from the Bhabha Atomic Research Center in Bombay.

Negotiations for a seventh instrument from an Italian group, though not concluded, are said to be promising. The biggest hope is that West German researchers, who have been among the most creative instrument developers, would join in. They are driving hard to get approval for their own pulsed source, the SNQ which would be built at Jülich and which would exceed the SNS in both neutron output and cost, and may well need a place to hone their experimental techniques pending construction or go to if the project fails to get the go ahead.

American and Japanese participation may also eventually come. In the United States, however, an upgrade project at the Los Alamos National Laboratory, scheduled for completion next year, has the potential for turning the present pulsed source there into one only a factor of 2 less powerful than the SNS, although target and instrumentation development has been slow, and a new experimental hall that neutron scatterers regard as essential to exploitation of the facility remains unfunded.

In sum, while Rutherford's SNS is a curious mixture of old and new, promise and peril, the overall facility is impressive, bodes well for European neutron scatterers, and gives their American colleagues a challenging target.

—**Arthur L. Robinson**

Additional Reading

1. *Current Status of Neutron-Scattering Research and Facilities in the United States*, available from National Academy Press, 2101 Constitution Avenue, NW, Washington, DC 20418.
2. *Physics Today*, January 1985 (special issue on neutron scattering).

Cosmic Cube Goes Commercial

Concurrent processing—the effort to create very fast computers by putting many processors to work in parallel—has finally begun to enter the marketplace: the Intel Corporation has announced a commercial version of the "Cosmic Cube," which has been under development for several years now at the California Institute of Technology and which has inspired quite a bit of enthusiasm among the researchers there. In its incarnation as Intel's "iPSC" line, the Cube will provide up to one third the power of a conventional supercomputer at roughly one tenth the cost.

While the Cube is only one of dozens of parallel designs now under development around the world, the theory and practice of concurrent processing is still very much in its infancy (*Science*, 10 August 1984, p. 608). Thus, Intel has explicitly tailored its machines for the research and development communities. "We want this to be the 'Access' machine," says Intel vice president Edward Slaughter, "the computer that people can get their hands on, where they can try things out and learn what can be done with parallel processing."

In fact, Caltech's original Cube has already established a remarkably good track record for that sort of thing. As developed by Charles L. Seitz, Geoffrey C. Fox, and their colleagues, it consists of 64 small computers, each of which is roughly equivalent to an IBM Personal Computer. These 64 processors are then linked together as if they were the corners of a six-dimensional "Boolean hypercube." Thus the name. (In two dimensions, four computers would simply be linked in a square; in three dimensions, eight computers would be linked as the corners of an ordinary cube; and so on.)

One of the first research applications of the Cube was a numerical calculation in quantum chromodynamics programmed by Caltech physicist Steven Otto. It ran for an accumulated total of 2500 hours, and showed for the first time both the short-range Coulombic forces and the long-range constant forces between quarks.

With that as an inspiration, other Caltech researchers have begun to develop concurrent algorithms for problems in high-energy physics, astrophysics, quantum chemistry, fluid mechanics, structural mechanics, seismology, and computer science. In fact, says Seitz, it is rather surprising to see just how many problems can be attacked with parallel algorithms once people start to think about it.

Intel, which donated processor chips to the Caltech team for the original Cube, has upgraded its commercial version to have as many as 128 processors, each somewhat more powerful than an IBM PC-AT. Provision has been made for the users to design and incorporate their own special-purpose boards. And the company is forming its own in-house group to work with the users in developing applications.

"It's a big risk for Intel," says Alvin Thaler, who is in charge of the National Science Foundation's program to put advanced computers in the hands of mathematicians, "but it's a very exciting development for the academic community."—**M. Mitchell Waldrop**