NOBELISTS BROCKHOUSE AND SHULL GAVE NEUTRON SCATTERING A JUMP START

More than 40 years ago Bertram N. Brockhouse and Clifford G. Shull started working separately at two of the world's first nuclear reactors, exploiting the opportunities to do basic research with the relatively large fluxes of neutrons from those machines. Their efforts helped launch the technique of neutron scattering, which is now widely used to study materials: Being uncharged, neutrons penetrate deeply to interact with the atomic nuclei of a sample, and having a magnetic moment, they also probe its magnetic structure. Today neutron scattering occupies thousands of researchers in condensed matter, materials physics, chemistry, biology and engineering (see PHYSICS TODAY, November, page 17).

To honor their "pioneering contributions to the development of neutron scattering techniques for studies of condensed matter," the Royal Swedish Academy of Sciences has awarded Brockhouse and Shull the 1994 Nobel Prize in Physics. In particular the academy cites Brockhouse, emeritus professor of physics at McMaster University in Hamilton, Ontario, Canada, for "the development of neutron spectroscopy" and Shull, emeritus professor of physics at MIT, for "the development of the neutron diffraction technique." In a more colloquial restatement of the prize citation the academy says that Shull laid the path for studying the structure of materials while Brockhouse developed tools for exploring their dynamics.

Elastic scattering

Shull arrived at Oak Ridge National Laboratory in 1946, joining Ernest O. Wollan, who was already attempting to study neutron diffraction patterns at the graphite reactor completed at the lab in 1943. (During the war years the reactor had produced the first measurable quantities of plutonium.) By that time it was established that neutrons are diffracted by crystals, just as x rays are, and that they exhibit a Bragg reflection, in which neutrons of a given wavelength (and hence energy) are diffracted by crystal planes at a unique angle. But it was not yet known whether neutrons would be a useful quantitative probe of matter, as x rays had proved to be.

Wollan, who had done thesis work under Arthur Compton at the University of Chicago on the scattering of x rays by gases, brought two gifts to the study of neutrons. The first was his spectrometer from Chicago, with rotatable supports for both sample and detector. Between the reactor and the spectrometer he placed a sodium chloride crystal, and using Bragg reflection from this monochromator he was able to select neutrons with a single energy from the continuous spectrum of neutrons in the beam. The basic arrangement for studying the elastic scattering of neutrons today is not much different.

The second gift Wollan brought from x-ray scattering was the technique of powder diffraction, in which one averages over all orientations of the tiny crystals making up a powder. This method avoids the extinction problem that arises within a larger, single crystal as a result of scattering. Using powder diffraction was a key step, explains Mike Wilkinson, who has worked on neutron scattering at Oak Ridge since joining the lab in 1950, because researchers in the early days were not able, as they are today, to correct in a quantitative way for extinction effects.

Groups at other nuclear reactors had also started to study neutron diffraction, but, notes the Nobel citation, the Oak Ridge group "proceeded most purposefully and achieved results with surprising rapidity." Shull told PHYSICS TODAY that he greatly regrets that Wollan, who died in 1984, did not live to share the Nobel Prize.

In the earliest years of their collaboration Wollan and Shull concentrated on unraveling the factors that affect the neutron scattering amplitudes of various nuclei and their consistency from one material to another. The two summarized their findings in papers in 1948 and described them in more detail in a 1951 paper in which they reported the scattering characteristics of some 60 different nuclei. These data established that the neutron scattering length is the same for a given nucleus independent of its crystalline environment; for example, sodium scatters neutrons just as strongly whether it is in sodium chloride, sodium hydride or sodium bromide. Thus neutron scattering was found to be a useful quantitative technique not only for determining scattering amplitudes of nuclei but also for using those amplitudes to determine the structure of materials.

One of the most significant findings in these studies was that the hydrogen atoms, which are virtually invisible to x rays, have a recognizable scattering amplitude and so are readily identified with the neutron scattering technique. Thus the technique complements x-ray studies of biological, organic and many inorganic molecules. Moreover, the scattering amplitude for deuterium differs in both magnitude and sign from that of hydrogen, and such isotopic differences surface in many other elements. These differences enable one to extract information by means of a method of isotope substitution.

Magnetic structures

In the late 1940s and early 1950s Shull and Wollan, together with Wallace Koehler and J. Samuel Smart, also explored what one could learn about magnetic materials by exploiting the neutron's magnetic moment. They were guided by the theoretical work of Otto Halpern and Montgomery Johnson, who in 1939 had predicted that the magnetic scattering of neutrons from paramagnetic materials would show up in the background of the neutron diffraction pattern as a diffuse scattering with an angular dependence. Although initially dubious about whether they could sort out this signal from the diffuse background, Shull told us, the Oak Ridge researchers were in fact able to study the paramagnetic scattering in a number of materials.

In the course of this work they came up with the first experimental demonstration of the existence of antiferromagnetism, which had been predicted by Louis Néel. At first the evidence came in the form of two puzzles: Why did they see anomalous diffraction peaks at room temperature for the iron oxide Fe_2O_3 but not the expected paramagnetic scattering? And why did the intensity of the paramagnetic diffuse scattering pattern for manganous oxide (MnO) have a broad maximum away from the forward direction? Shull recognized that the pattern seen in manganous oxide was characteristic of short-range order. When his group lowered the temperature of this sample, the diffuse scattering faded, but sharp peaks appeared at unexpected positions, like the anomalous peaks seen in the iron oxide. Conversely, when they raised the temperature for the iron oxide, the anomalous peaks disappeared. The materials were going through transitions from short- to long-range magnetic order. Shull's group interpreted the latter state as antiferromagnetism.

Born in Pittsburgh, Pennsylvania, in 1915, Shull earned a BS from Carnegie Institute of Technology in 1937 and a PhD in physics from New York University in 1941. Shull then worked at the Texas Company in Beacon, New York, before moving to Oak Ridge. Shull had risen to chief physicist at Oak Ridge by the time he left for MIT in 1955. Until he retired in 1986, he continued to pursue neutron scattering research, leading the way in high-precision measurements of the fundamental properties of neutrons.

Clifford G. Shull (right) and Ernest O. Wollan shown around 1950 with a spectrometer they used for neutron scattering studies at Oak Ridge.

Inelastic scattering

Word of the work that Shull and Wollan were doing at Oak Ridge reached Brockhouse just as he was completing his PhD in 1950 at the University of Toronto. It was one factor affecting his decision to accept an offer from the Chalk River Laboratories in Ontario, Canada, to do research at the NRU reactor there. Brockhouse's mentor at Chalk River was Donald G. Hurst.

In the late 1950s the idea was circulating that one might be able to glean information about the phonons in solids by studying the inelastic scattering of neutrons. Phonons are quanta of vibrations within a crystal lattice whose excitation energies are comparable to those of slow neutrons. If researchers could measure the changes in momentum and energy as a neutron scattered from a solid, they should be able to trace a dispersion curve (frequency versus wavenumber) for the phonons—or other collective excitations such as magnons or spinons. From the phonon dispersion curve one could then infer much about the material properties. The dream of measuring such curves was enticing, but the reality was bleak: Getting the requisite intensity was deemed nearly impossible. Brockhouse, however, reasoned that if it could be done anywhere, it would at the NRU reactor, which had the highest usable flux of any reactor at the time. Brockhouse developed several proposals for measuring the inelastic scattering of neutrons, one of which was a triple-axis spectrometer. That instrument proved to be a winning idea.

The triple-axis spectrometer resolves the energy and momentum of the outgoing as well as the incoming neutron. The wavelength and direction of the incoming neutron are selected by a monochromator, just as they are in the spectrometers for elastic scattering. A second monochromator selects an outgoing neutron with a given wavelength and direction. The intensities of these neutrons are then measured with a detector. (The three axes that give this spectrometer its name are those about which the sample and the initial and final monochromators rotate.)

There are other designs for studying inelastic scattering, many using combinations of choppers (to select neutrons of a given velocity) and time-of-flight measurements (to determine the velocities). Those who have contributed such designs include Donald J. Hughes and Harry Palevsky of Brookhaven National Laboratory, Bernard Jacrot at Saclay in France and Peter Egelstaff, Raymond D. Lowde and others at the Harwell Laboratories in England. But the triple-axis spectrometer remains the workhorse of inelastic neutron scattering. Robert Birgeneau of MIT, who cut his teeth on neutron scattering at Chalk River, commented to PHYSICS TODAY on how little the instrument has changed since Brockhouse designed it.

The Chalk River group had to clear some hurdles to make the triple-axis spectrometer a practical device. Among the essential ingredients were large, single-crystal aluminum monochromators, made by David G. Henshaw. Others included techniques such as the use of thin samples to reduce the background of multiple scattering.

The method of constant Q

Not only did Brockhouse design a valuable instrument, but he made the mental leap into reciprocal space and suggested operating the instrument to collect only data points corresponding to a fixed value of $\mathbf{Q}$, the difference in wavevector $(k_i - k_f)$ between the ingoing and outcoming neutrons. This method of constant $\mathbf{Q}$ is an extremely efficient way to focus only on

Bertram N. Brockhouse lecturing at Chalk River in the early 1960s.

the data that you really want. To explain its utility, Gerald Dolling of Chalk River, who worked with Brockhouse in the early 1960s, invokes an analogy to hunting geese. If you wanted a particular goose out of a thousand flying overhead, you might shoot down a whole bunch with a shotgun and hope that your prey was among them—or you might get a high-powered rifle with a telescopic sight so that you could pick off just the bird you want. Brockhouse's method is that accurate firearm. One operates the spectrometer so that one collects only data corresponding to a particular value of **Q**, which for theoretical simplicity is often selected to be a symmetry direction for the crystal in **k** space. Determining the instrument settings for constant **Q**, of course, requires a lot of advance calculations; in the early days, Brockhouse told us, they had to set as many as 90 switches for each run. Eventually, however, Ed Glaser at Chalk River helped them to build computer controls.

By 1954 the triple-axis spectrometer was ready to yield quantitative data, and Brockhouse participated with others at Chalk River in exploiting his creation. In 1955, with Alec T. Stewart, he published dispersion curves for aluminum and vanadium. With his colleagues Brockhouse also used samples of magnetite to study magnons, collective wave motions among the atomic elementary magnets. And while participating in Chalk River's program on low-temperature liquids, Brockhouse found that one could use neutrons to study correlation functions, that is, how the "memory" of any particular arrangement of atoms in a fluid gradually disappears with time. Brockhouse's colleagues in the 1950s included David Woods, William Cochran, Roger A. Cowley, P. K. Iyengar and Noel K. Pope. Dolling, who was a student at Harwell in the 1950s, said that he decided to join Chalk River because Brockhouse kept beating him to results on whatever sample he chose to study.

Born in Lethbridge, Alberta, in 1918, Brockhouse did not start his formal training in physics until the age of 27. He earned a BA from the University of British Columbia in 1947 before getting his PhD from Toronto in 1950. Brockhouse stayed at Chalk River until 1962, when he went to McMaster. He served as physics department chairman there from 1967 to 1970 and became an emeritus professor in 1984.

—BARBARA GOSS LEVI

DISTANCE TO VIRGO KICKS OFF HST ASSAULT ON THE HUBBLE CONSTANT

One of the "Key Projects" intended for the Hubble Space Telescope from the start was to pin down the distance to the Virgo cluster by measuring Cepheid variable stars in that massive assemblage of galaxies some 50-million light-years away. Cepheids are the primary yardsticks for astronomical distances beyond the reach of parallax measurement. The inability to determine cosmologically relevant distances with confidence has been the principal source of confusion in our knowledge of H_0, the Hubble constant. The HST's measurement of Cepheids in the Virgo cluster was to be the opening salvo in an assault that would soon pin down this fundamental parameter of cosmology to within 10%, once and for all. Estimates of the Hubble constant in recent years have differed by as much as a factor of two, and the stakes are high. The reciprocal of H_0 is, after all, the first approximation to the age of the universe.

The intrinsic luminosity of a Cepheid variable star is a universal, monotonically increasing function of the period (typically weeks) of its highly regular brightness oscillation. (See the figure on page 20.) Thus one gets a distance determination simply by measuring a Cepheid's period and *apparent* average brightness. In galaxies beyond a few million light-years, however, ground-based telescopes can measure only the very brightest Cepheids, and the impaired optics of the orbiting Hubble Space Telescope, as originally launched in 1990, restricted its Cepheid measurement range to about a third of the distance to the Virgo cluster.

But now, with the corrective optics of the HST's new Wide Field–Planetary Camera, installed by visiting astronauts just a year ago, the Key Project group led by Wendy Freedman (Carnegie Observatories, Pasadena, California) has managed to obtain high-quality light curves for 20 Cepheids in M100, a prominent spiral galaxy in the Virgo cluster. These observations[1] yield a distance of 17.1 megaparsecs to M100, with an uncertainty of only 10%. (A megaparsec is 3.26×10^6 light-years.)

The Hubble constant

Hubble's law of universal expansion asserts that at sufficiently large distances all celestial objects are receding from one another with velocities proportional to the distance between them. H_0 is the universal proportionality constant. To determine the Hubble constant from the observation of a remote object, one must have both its recessional velocity, measured by redshift, and some independent measure of its distance. In recent years contending observers have argued for values of H_0 as low as 50 and as high as 90 km/sec per megaparsec. Values higher than about 50 make cosmologists nervous, because they seem to imply a universe younger than the oldest stars in our own Milky Way. (See PHYSICS TODAY, November 1992, page 17.)

The Key Project's Cepheid measurement of the distance to M100 yields a value of 82 ± 17 km/sec-Mpc for H_0. That number comes from using the average redshift of many galaxies in the Virgo cluster. The redshift of M100 alone, or of any other single galaxy in Virgo, is likely to have a significant non-Hubble component due to internal motion within the cluster. Thus the principal uncertainty in this new determination of H_0 comes from not knowing the position of M100 relative to the central core of the widely dispersed Virgo cluster. There is, however, some evidence that M100 is neither very far