NEUTRON AND OTHER STORIES FROM CHALK RIVER

by William J.L. Buyers

Here are a few stories about just a few of the scientists that I know something about. It is a personal selection that illustrates how great doers worked with simple means.

BERTRAM BROCKHOUSE

Bert Brockhouse is AECL's most famous pioneer in the field of science. The neutron was 18 years old[1] when he arrived at Chalk River. Donald Hurst, who hired him, and who passed away in 1999, had already built a neutron diffractometer at NRX, and told Bert to do something interesting with neutron beams. He did.

In 1950, Atomic Energy of Canada Limited (AECL) hired a scientist who created a new field of science using thermal neutron beams, and who was co-winner of the 1994 Nobel Prize in Physics.

The triple-axis spectrometer he invented showed that thermal neutron beams from a reactor could reveal the motions of atoms and the precessions of their atomic magnets. Today neutron scattering applications have expanded well beyond physics to encompass chemistry, biology, earth sciences, materials science, and engineering. Only because Bert built a laboratory in fundamental neutron science was it possible for these practical applications to emerge. Of course, he did not "build" a laboratory – he simply did the next experiment that needed doing. He was filling in pieces of what he has called the "Grand Atlas" of the physical world. [1]

Long before the triple axis spectrometer, one of Bert's first experiments, with Myer Bloom and Don Hurst, verified, through scattering, the famous Breit-Wigner formula for heavily absorbing elements. Myer Bloom, who came as a summer student that year and worked on this tough topic, relates that Bert had to finish the project off for him. Later Bert and Don observed the effect of thermal vibrations on the scattering cross-section of light and heavy elements (aluminum, graphite and lead). To do this a beam of 0.35 eV neutrons, of which there are only a few from a reactor, was scattered through a right angle by the material and then travelled through cadmium before reaching the detector. Now cadmium is almost black to slow neutrons – it is used to block the beam! However, because its absorption varies inversely as the neutron velocity, the cadmium transmitted fewer neutrons if they had been scattered with reduced velocity. A low velocity showed that the neutrons had lost energy by creating phonons. This was the first quantitative experiment in slow neutron spectroscopy and was published in *Physical Review*. [2]

By 1951 scientists in France, Britain and the U.S.A. had started to build time-of-flight spectrometers to measure the speed of the neutron before and after scattering. Brockhouse and Hurst thought that a time-of-flight spectrometer would be too technically demanding, and they decided to build a crystal spectrometer. Keeping things simple, a Brockhouse characteristic, was a wise choice. A war-surplus Bofors gun mounting was adapted for the crystal table. If he had chosen instead to spend lots of money, he might not have taken the path that led to the triple-axis crystal spectrometer, to his seminal discoveries, and ultimately to Stockholm.

How does neutron scattering directly reveal the

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[1] If the neutron had not been discovered by Chadwick in 1932, it would have been invented, according to Bert Brockhouse.

structure and dynamics of materials? One neutron property is the basis for diffraction, elastic scattering, and structure determination:

> *The wavelengths of neutrons from a fission reactor moderator are a beautiful match for the typical spacing between the atoms in materials.*

Bert Brockhouse focused on another beautiful property of neutrons from a reactor:

> *The neutron energies are a very good match to the energies of atoms as they vibrate about their equilibrium positions.*

When a neutron is scattered, it can give a kick to, or be given a kick by, the moving atoms. It can then leave the sample at lower or higher speed and in a different direction than the elastic Bragg scattering. A vibration of a crystal lattice is similar to a sound wave, but its wavelength can be as short as the distance between atoms.

The frequency of such atomic vibrations is extremely high, more than a THz (10^{12} cycles per second) or tens of meV in terms of energy. Bert and others realised that if the frequency of atoms in solids could be measured it would give the force or spring constant between two atoms. To determine the interatomic forces directly would represent a major breakthrough in our understanding of all kinds of condensed matter.

For short vibration times, that is, for high frequencies, the neutron energy will undergo a large shift, while, for motions involving long times, the neutron energy shift will be small. This is similar to the diffraction from structures, where the diffraction pattern is big when the spacing is small. So the world of scattering is somewhat like what Alice saw through the looking glass - the reciprocal of the world of space and time. Bert was very good at touring his visitors through the concepts of neutron science. His colleague, Guiseppe Caglioti, who returned home to build the neutron program in Italy said [3]

> *"Brockhouse was a real Cicerone to all the subtleties of reciprocal space, for all the researchers converging to his group from Canada and from all over the world."*

The first reliable measurement of the spectrum of phonons, the name for quantized vibrations of a crystal, was made in 1955 for aluminum. It was an unequivocal demonstration that short wavelength vibrations existed in a metal. By 1958 Brockhouse had published the most complete set of data for all three symmetry directions in aluminum. He succeeded partly because he could select the momentum with the triple-axis crystal spectrometer, and partly because Chalk River then had the highest flux of thermal neutrons in the world.

One of Bert's collaborators was Alec Stewart who became an international leader on positron research in solids. At Chalk River, scientists Alec Stewart, Bob Bell, and Bob Graham were the first to have shown that positron annihilation could be a useful tool in solid-state research. They discovered, by 3-photon coincidence, that long-lived positronium formed in interstitial positions in amorphous insulators, thereby confirming an earlier conjecture by Bob Bell, Bob Graham and Howard Petch that was based on the less direct observation of a long lifetime. When NRU went down for a period, Alec Stewart, on leave from Chalk River at Dalhousie University, supervised an M.Sc. student called Ralph Green. Their measurements were the first to clearly show that the angle between pairs of gamma rays arising from annihilation of free positrons with electrons was a measure of the electron momentum distribution in solids. Ralph went on to become Vice-President for Research at AECL. Alec pioneered this angular correlation method, now in use throughout the world, and applied it later at Chapel Hill and Queen's University. But his first love had been neutrons. Alec's seminal article on neutron scattering, with Bert Brockhouse, in *Reviews of Modern Physics* [4] helped bring scientists from all over the world to Chalk River to work in Bert's small group.

I read the Brockhouse and Stewart review with amazement while I was a graduate student in Scotland. I had just completed years of hard thesis work to derive the phonon frequencies in rock salt from the intensity of X-ray scattering. In order to obtain the one-phonon thermal diffuse scattering I had to subtract large corrections for Compton, multiphonon, absorption and background effects. The intensity had also to be put on an absolute scale. Only then could measurements at two equivalent momenta be combined to extract the acoustic and optic modes of this diatomic, but simple, crystal. Bert and Alec's review showed that phonon peaks could be seen directly in the neutron spectrum since the spectrum of scattered energies could easily be analysed. It seemed they only had to plot their data by hand to get a dispersion curve ready to be sent off to the journal.
I could not believe that life could be so simple, so
I came to Chalk River and found out it was true!
Neutron scattering was really easy.

Fig. 1 **Bert Brockhouse looking at the triple-axis spectrometer. The neutron beam comes from the left out of a large shielded drum containing the monochromator. The cryostat and analyser arm are carried on a Bofors gun mount driven by steel belts. To the right is the shielding around a long BF3 neutron detector. The "swipes" were taken not by frustrated physicists, but by health surveyors ensuring that the shield was clean.**

By 1959 Bert had built a Constant-Q triple axis spectrometer (Figure 1) which could be programmed to look for an excitation at a controlled momentum, Q, and independently scanned to find its energy. There to help him was Bill McAlpin who, with his Scottish upbringing on the Clyde, designed spectrometers to battleship standards; some are still running today. The Brockhouse Triple-Axis Constant-Q spectrometer is now in use at every major international neutron laboratory. Its advantage is that it is flexible enough to be adapted to a wide variety of experiments. Bert also built the first Rotating Crystal Spectrometer. It used time-of-flight to measure the velocity and therefore the energy of the neutrons before and after scattering. Scientists returning to their own countries built instruments based on what they saw at Bert's laboratory.

"Programming" of a triple-axis spectrometer was initially done by an array of 52 rotary switches preset to go through an energy scan of 26 points. An ac motor drove the primary monochromator angle linearly in increments of multiples of 1/8 degree. Two secondary motors were slaved to it by steps set by switches that could be varied throughout the 26 steps, so as to approach closely the non-linear solution of the constant-Q equations. Even stepping motors and encoders had a 1950's analogue. A motor drove each angle with a steel belt that carried a cam with peripheral indentations into which a relay could drop and give a pulse. When the number of relay pulses reached the number set on the 52-switch controller, the motor power was switched off. At an international conference where this non-linear control was reported, it was jokingly described as a triumph of experiment over mathematics. One of the best things about Bert's large "programming" box, was that his technician, Ed Glaser, got it going in six months. Today, I don't think you can interface a control system to any complex device nearly so fast. Besides, there are protocols to write, environmental assessments to obtain, project managers, accountants, human factors, ………. It was a lot easier to get things done then!

Just as the neutron can scatter from nuclei, its magnetic moment enables it to scatter from the atomic magnetic moments carried by the spin of the electrons in solids. In 1958 Brockhouse carried out the first application of crystal spectrometry to a magnetic system. Bert showed that, in magnetite, "the excitations were in the spin system itself", a result that first confirmed theoretical predictions that the spin excitations occurred in quantized packets called magnons.

The discoveries of the existence of phonons in metals and of spin waves in magnets were qualitative breakthroughs. Today we are more concerned with quantitative science, where the conceptual framework has largely been established. Bert was always concerned as to whether a new concept would remain on the map of the physical world or would disappear with time. Most of his ideas are still with us.

Today neutron beams and instruments are found in large laboratories visited by "users" from the universities and industry. Compared with Bert, who invented new instruments and did the science at the new frontier, today's scientists can be said to have a "free ride". They should be glad he cut a path through the jungle.

After he arrived, in 1958, Dave Woods was Bert's closest collaborator. Bill Cochran came from Cambridge for a year's sabbatical and, with Dave and Bert, developed the famous "shell model" for lattice vibrations. [5] This Woods-Cochran-Brockhouse shell model has nothing to do with the nuclear shell model, but is a simple way of seeing how the movement of each atom polarises its outer shell of electrons so as to communicate the force to the next atom by distorting its shell. Prior to that even the simplest alkali halides could not be understood because their short wavelength vibrations were much softer than expected from a simple Hooke's Law (Born-von Karman) effective force between the atoms. The Cochran theory also accounted for the Lyddane-Sachs-Teller relation between the optical mode vibration frequencies and the dielectric constant. Yes, Teller did a few things other than design bombs!

During the years at Chalk River, before he went to McMaster in 1962, Bert was well known as a singer. He took part in the local Gilbert and Sullivan productions. And he was known to wander about the reactor hall exercising his vocal chords to the surprise of the operators in white overalls. He is said to have occasionally practised on the midnight bus going back from "the Plant" to Deep River.

Bert trained many fine students. According to Eric Svensson, he would get them in a room and tell them what they had to do to succeed at physics using the Brockhouse Rule:

> *"An experimentalist has to get his data right."*

(Some of the students thought this meant it was all right to screw up the analysis!)

and the Brockhouse Manifesto:

1. *Being a Graduate Student is not a 9 to 5 job.*
2. *Necessary work takes precedence over coffee breaks and reading newspapers.*
3. *Use your intuition if you have a good one! This can save you all kinds of messy algebra that you might get wrong anyway.*

Anyone who talked with Bert knew he had superb intuition. Bert's work led to a present community of about 10,000 neutron users world-wide who continue to be starved for strong neutron sources. The proposed Canadian Neutron Facility will meet part of the need, particularly in North America following the 1999 announcement not to restart the High Flux Beam Reactor (HFBR) at Brookhaven.

ROGER COWLEY

In the early 1960's Bill Cochran sent his graduate student Roger Cowley from Cambridge to Chalk River to do some of his thesis research on the ferroelectric $SrTi0_3$. Watson had much earlier asked Cochran, the Cambridge expert on X-ray diffraction, what might cause the strange spots on his X-ray pattern from DNA. Cochran is said to have replied "have you tried a spiral?" For ferroelectrics, Cochran had surmised that their transitions on cooling to a phase with a net ordered electric dipole moment, were caused by the softening of a lattice vibration frequency. Roger Cowley obtained the neutron data that proved this. Moreover he brilliantly developed the theory of anharmonic interactions of phonons in crystals into a practical form, where he could calculate the dynamics of phase transitions, the renormalization of phonon energies and lifetimes, and the specific heat and thermal expansion. [6] This theory accounted for the temperature dependence of not just ferroelectrics, but insulators and metals.

Roger returned to Chalk River as a research scientist in 1964. With Gerald Dolling, who had worked with Bert on semiconductors, the first magnon-phonon coupling was observed, in uranium dioxide (a highly appropriate material to work on at Chalk River!). With others at Chalk River, the zero point fluctuations of antiferromagnets were seen, and the fundamental studies of magnetism were begun. With Dave Woods, Roger mapped out the spectrum of the quantum fluid liquid helium, and found the two-roton scattering.

From what is now called deep inelastic scattering, they obtained the first hints of the zero-momentum condensate of Landau, whose magnitude was later obtained accurately by Eric Svensson. In 1970 Roger took up a Chair at Edinburgh University. He is now head of Physics at the Clarendon Laboratory, Oxford, but maintains to this day a Chalk River connection.

When equipment like the early temperature controller did not seem to work, Roger would walk away saying "there are some things I choose not to know about". He could afford this luxury because technical experts like Harold Nieman and Ed Glaser were around to solve such problems. One of the technicians was Rick Dutkiewicz, whose fame came not through neutrons but later as bass guitar in the Gordon Lightfoot band.

JOHN HILBORN

Most physicists like to work on exotic ideas like the non-linear sigma model, rather than solve the problems encountered in inventing, developing and building a research reactor. A person who got interested in physics after learning on his first job how to measure radioactivity in the Eldorado Mine at Great Bear Lake is John Hilborn. John got the job by responding to an advertisement in the Globe and Mail.

After an interview in a booth at the 1949 Canadian National Exhibition, John headed north. In those days you had to make your own Geiger counters from glass bodies and find a gas filling that worked.

John belongs to the breed of reactor physicist-designer who relied primarily on simple hand calculations and intuition rather than on complex computer models. A lot of reactor design is knowing about plumbing and water flow as well as the behaviour of neutrons. The SLOWPOKE - a reactor with a passive safety system, natural convection and only one moving part - is his invention.

The SLOWPOKE story starts in Los Alamos, with the publication of a paper describing a beryllium-reflected critical assembly requiring less than 300 grams of U-235. This surprising result led John Hilborn to the conceptual design of the SLOWPOKE research reactor. Conceived as a simple, low-cost neutron source, SLOWPOKE is a Canadian compromise. It was smaller than the American TRIGA reactor, but powerful enough to play an important role in teaching and research at five Canadian universities and one in the West Indies, from the early 1970's to the present day. At a power level of only 20 kW, SLOWPOKE produces a thermal flux of 10^{16} n/m^2.s at five sample sites. The resulting ratio of neutron flux to fission power is the highest of any research reactor in the world. The unique core design is such that the reactor is inherently safe with respect to the most common mechanical and electrical faults. Consequently it requires only one motor-driven control device which is automatically activated by one neutron detector. There are no additional safety devices, and no pumps since it is convection cooled. The reactor is continuously monitored at a remote location to operate and is licensed to operate without a person in the reactor room. The power level is intrinsically limited to safe levels.

John recalls he had some anxiety during the final testing of the prototype at Chalk River. These tests were designed to prove the SLOWPOKE did not need an engineered safety system. But to carry out the tests, the reactor was provided with conventional engineered safety devices that would shut the reactor down instantly before the power reached dangerous levels. The tests proved beyond doubt that SLOWPOKE's inherent safety characteristics were entirely adequate and agreed with predictions. The engineered safety system was unnecessary and could be removed. John did not get much sleep the night before that action was scheduled to take place. Had they thought of all possibilities? Had they overlooked anything? After all, no nuclear reactor had ever been operated without an engineered emergency shutdown system. The redundant safety devices were duly removed, the final tests were completed as planned, and for almost 30 years all of the subsequent SLOWPOKE reactors have operated safely and reliably.

The original fuel was an alloy of highly enriched uranium and aluminum that would last about 20 years. Each reactor core required approximately one kilogram of enriched uranium, which was obtained from the United States under long-standing agreements. However, when the core for Jamaica was ready for shipment, the U.S. State Department suddenly intervened, claiming that the proposed sale of highly enriched uranium violated their policy of non-proliferation. They wanted AECL to use a low-enriched fuel that had just been developed at the Argonne National Laboratory. When the Canadians pointed out that the physics of the core did not permit the use of the Argonne fuel material, they suggested that AECL's calculation must be in error. It was not. After a year of wrangling, AECL agreed to develop a special low-enriched fuel for all future SLOWPOKE reactors provided the ready-and-waiting enriched core for the Jamaica reactor could be released for shipment. In retrospect the action of the State Department turned out to be a blessing in disguise. The new low-enriched fuel, designed specially at Chalk River, not only works, but has been found to be technically superior to the original SLOWPOKE fuel.

AECL's Commercial Products Division (later Nordion International) manufactured and installed eight SLOWPOKE reactors, but, in spite of intense marketing efforts, they were unsuccessful in selling SLOWPOKE internationally. The larger and more costly TRIGA reactor dominated the market, and we can only speculate that, if SLOWPOKE had been available ten years earlier, many more SLOWPOKES would have been sold. It is somewhat ironic that China never purchased a SLOWPOKE reactor, but has been marketing a close copy of SLOWPOKE for the past ten years.

John also invented the Self-Powered Neutron Detector, a simple solid-state device for monitoring thermal neutron flux inside a nuclear power reactor. At Ontario Hydro's CANDU generating stations they are known as Hilborn detectors.

He read about this device in a Russian scientific journal and, by choosing suitable materials that could with-stand the intense radiation, adapted it for measuring neutron flux inside a nuclear reactor. Within a few days he was able to test a simple prototype in the NRX reactor at Chalk River, and was amazed to discover that it produced a direct current of microamperes without amplification. Within a few months he measured a neutron flux profile in the NPD power reactor [2]. To carry out that kind of prototype development and in-reactor testing today would take years of preparation and a mountain of paperwork.

The device itself is incredibly simple. In essence it is a coaxial cable a few millimetres in diameter, comprising a central wire, ceramic insulation, and a metal jacket. When exposed to thermal neutrons, the central wire becomes radioactive and emits energetic electrons (beta particles) which penetrate the insulation and generate a continuous direct current proportional to the neutron flux. If the half-life of the emitter material is short, the electrical signal from the coaxial cable will rise and fall with the neutron flux and power of the reactor. The speed of the response is enhanced by secondary electrons from prompt neutron-capture gamma rays.

John Hilborn was co-founder of a Canadian company that manufactured and sold Self-Powered Neutron Detectors under a government patent. The company is still in business today in Cambridge, Ontario. Meanwhile, other physicists continue to work on the non-linear sigma model! Both kinds of activities are of course worthwhile.

BORIS DAVISSON [7]

One of the important figures in the development of the CANDU reactor was Boris Davisson, who taught reactor physics at the University of Toronto to a generation of nuclear engineers in the 1950's and whose book Neutron Transport Theory [8] became the definitive treatise on the subject. Boris had an unusual background. Born and raised in Leningrad of a Russian mother and a Scottish father, Boris was somehow allowed to leave the Soviet Union in the late 1930's to study theoretical physics with Rudolph Peierls in Birmingham, England. In 1944 he joined the British-Canadian Atomic Energy Project at NRC's University of Montreal Laboratory, which shortly thereafter moved to the new Chalk River site. Boris returned to the U.K. in 1947 to work at the Atomic Energy Research Establishment in Harwell. Although non-political, he later fell victim to the cold-war hysteria that followed the Klaus Fuchs incident in Britain. No longer welcome in Britain because of his Russian background, nor in Russia because of his British background, Boris returned to Canada in 1954 at the invitation of the Head of the Physics Department at the University of Toronto, W.H. "Willie" Watson -- another expatriate Scot who had earlier been head of the Theoretical Physics Branch at Chalk River. Boris visited Chalk River frequently to collaborate on research with Steve Kushneriuk and others until his untimely death in 1961.

BRUCE BIGHAM

In the early 1970's, the Nuclear Physics group asked Accelerator Physics to develop a booster for the Tandem. They wanted to add energy of about 10 MeV/nucleon for heavy elements like uranium and up to 50 MeV/nucleon for lighter elements. There were several possibilities, but few that could be done simply and cheaply. In 1972, Harvey Schneider went to a magnet conference and heard some new ideas on how to make stable superconducting magnets that would not quench. One idea was to twist the superconducting filaments on the magnet winding. Harvey realised that it should now be possible to make an affordable superconducting cyclotron with an average field in the 5T region. John Fraser, Harvey Schneider and Bruce Bigham took the idea to the experts at Michigan State University (MSU) where Henry Blosser was very sceptical. Within months, however, he had his own project going at MSU and Chalk River co-operated with him throughout the 10 years of design and development.

Around that time Harvey and Bruce patented an idea for a small cyclotron for cancer treatments, with neutrons mounted on a gantry so that it could be rotated. It gave a forward beam of neutrons from 25 mA of 30 MeV deuterons on an internal target of beryllium. Henry Blosser built a similar one under licence from the Chalk River group that has treated prostate cancer patients in Detroit.

For the booster for the Tandem, Bruce and Harvey had

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2. The small Nuclear Power Demonstration reactor, a short distance west of Chalk River at Rolphton, was the first reactor to supply power to the Ontario grid.

to explore the options more widely than experienced builders, and this led to some unique features. They shimmed the magnet with an array of adjustable rods instead of coils. Clarence Hoffmann's extraction channel used both iron and superconducting coils to cope with the wide range of beam parameters. The RF accelerating structure is the only one to have had up-down resonators operating in 0 or π mode (the asymmetry averaged out for the beam) and the plunger for tuning them had unique sliding contacts. No one else managed to use a "weak" copper liner over the steel poles with a guard vacuum outside. The trim rods and the up-down resonators are unique to the Chalk River design. All of these features kept the cost down yet met the required wide range in operating parameters.

Isochronous cyclotrons are very intolerant of imperfections, requiring very careful trim rod settings. To change to a different ion requires changing the frequency, the field, and the field profile to take care of relativistic effects. A control computer was used to do this. With it Bruce Bigham spent many nights trying to set up beam patterns like that of the very first beam that had been accelerated, which John Ormrod had set up by field mapping. Bruce recalls that it wasn't until after he retired that Nathan Towne discovered the small error in the set-up software that had defeated him.

The robust magnet is probably the only one of the superconducting cyclotron magnets that never had a quench. This says something for Harvey's careful coil design and John Hulbert's cryogenics.

Like many others, Bruce is disappointed that, after the nuclear physics program was shut down in 1997, the Tandem Accelerating Superconducting Cyclotron (TASCC) facility was not converted to a proton therapy facility. He believes it would have cost little more money than it took to cut the cyclotron into small pieces and clear out the building. However, Bruce and the entire Chalk River accelerator team should take pride in their tremendous achievements, ever since the heady days of the Intense Neutron Generator in the 1960's, in the science and engineering of high-performance accelerators. To this day no nation has built a spallation neutron source that can come even close to the 65 MW power and steady-state 10^{20} n/m^2.s flux of the proposed ING design. The forefront today is only 2MW of pulsed neutrons from the spallation source that has just started construction in Oak Ridge at a projected cost of US$ 1.3 billion.

MORE PHYSICS STORIES FROM CHALK RIVER.

Many of the Chalk River physics highlights may be found in "Canada Enters the Nuclear Age" [9], and in histories of theoretical physics [10] and of accelerator physics [11].

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