NUCLEAR PHYSICS ACTIVITIES AT CHALK RIVER

by James S. Geiger and Tom K. Alexander

The initial focus of the wartime atomic energy project in Canada was construction of the ZEEP and NRX reactors. Upon completion of the NRX reactor, the NRC scientific staff and the UK attached staff were presented with the opportunity of using this new resource to tackle physics problems which its high neutron flux brought, for the first time, within experimental reach. NRX clearly outclassed any of the then available competitors as an experimental tool. Completion of the NRU reactor in the mid-1950's added to these capabilities. In addition to the reactor-based studies, one saw a variety of other studies undertaken. Accelerator-based studies evolved from those based on Cockcroft Waltons, to 3MV Van de Graaff studies, to 5 MV EN Tandem work, to 10 MV MP Tandem work and ultimately to the Tandem Accelerator Super-conducting Cyclotron (TASCC) facility. The EN Tandem installation, the first of its kind, placed the laboratory in another unique position, this time with a tool ideally suited to address low-energy heavy-ion reactions.

The laboratory staff had the benefit of a management that demanded excellence, provided the resources necessary to achieve excellence and that operated an internal refereeing system which insured that the publications that left the laboratory were of the highest quality.

The research programs had the benefit of a very strong laboratory infrastructure and strong support on both the financial and technical side. The infrastructure included a strong electronics group that developed state of the art automated data acquisition systems to support the research activities, a counter development group that custom built detector systems optimized for planned applications, and a radioactivity standards laboratory. It is noted that Lloyd Elliott arranged for the Reactor Operations group to set up a Van de Graaff operations section staffed by special operators and engineers to run and maintain the accelerator, thus freeing up the experimental physicists to devote full time to research. The Operations group was headed by Phil Ashbaugh and later by Neil Burn who, before he retired, saw it become a TASCC Division branch.

The laboratory staff had the benefit of a management that demanded excellence, provided the resources necessary to achieve excellence as noted above, and that operated an internal refereeing system which insured that the publications that left the laboratory were of the highest quality. Lloyd Elliott was Editor of the Canadian Journal of Physics (CJP) for several years, and strongly encouraged staff to publish in that journal, an action that contributed significantly to the prestigious nature of CJP. In the case of abstracts for meetings, where current practice tends to have them reflecting what the author hopes to achieve between the date of submission and the time of the meeting, if the data on which the abstract was based were not in hand, together with at least a preliminary analysis, the abstract did not see the light of day. In addition to Physics Division programs, the laboratory had strong programs in chemistry, metallurgy, biology, and reactor physics, and the 8:30 a.m. laboratory colloquia had the benefit of strong multidisciplinary attendance. The persons primarily responsible for maintaining this highly productive work environment through the 1950's and 1960's were W.B. Lewis and L.G. Elliott. Dr. D.A. (Daddy) Keys' visits to, and interest in, the individual research activities and their progress added a valued human touch. Experts were eager to

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respond to requests for assistance or special apparatus and their assistance frequently resulted in the project making a quantum leap forward. Such interactions often led to longer term collaborations and some of these will become apparent in the few examples of research described.

The experiences of one of the authors (TKA) when starting his employment career give some idea of the laboratory climate for a junior researcher. "In late 1955, I started work at Chalk River in Art Ward's Reactor Physics Branch. A year or two later, then in the Electronics Branch of the Physics Division, I became fascinated by the new transistors and their use in nuclear instrumentation as pioneered by the Branch Head, Fred Goulding. He and Art Ward totally changed the way I approached research. I know W.B. Lewis read some of my reports because he suggested ways to improve the electronics. Bert Brockhouse was the first to say the device we designed for him worked fine. We developed for the Physics group, among many new transistor devices, a two-parameter coincidence kicksorter (pulse-height analyser), employing Lloyd Robinson's excellent ADC's (analogue-to-digital converters) and a pulse-shape discriminator to separate neutrons from gamma rays detected in organic scintillators like stilbene and liquid NE 213. In the summer of 1962, I got to use both instruments and the world-famous angular correlation methods of Litherland and Ferguson, in a very successful EN Tandem experiment to measure the spins and lifetimes of excited levels of ^{17}O and solve a vexing puzzle in the spectroscopy of this important nucleus. The work was done with the collaboration of Cyril Broude and Ted Litherland and formed part of my Ph.D. thesis with the group of Ken Dawson, Croy Neilson and Jack Sample at the University of Alberta."

An early experiment that drew international attention was Geoff Hanna and Bruno Pontecorvo's determination of a 500 eV upper limit on the rest mass of the neutrino. They added reactor-produced tritium to the fill gas of a proportional counter and determined the shape of its beta spectrum from the pulse height spectrum. The experiments made use of a 30-channel kicksorter built by Geoff Hanna and Carl Westcott that was superior to anything available at Los Alamos at that time. Their 500 eV limit came from the shape of the spectrum near the end point.

Another experiment of general interest to the physics community was John Robson's determination of the half-life of the neutron. In this case, the quantity measured was the beta spectrum that characterizes the neutron decay. The measurements were done with a beta spectrometer mounted at the reactor face. Reactor-produced neutrons provided the source and events characterizing neutron decay were selected by requiring that a proton, detected in a secondary detector viewing the source region, be in coincidence with the decay electron. The decay energy was measured and the 12.8(2.5) minute half-life followed from beta-decay theory. John Robson and Mac Clark went on to measure the proton-electron angular correlation in the neutron decay.

Neutron scattering studies were started in the 1940's and rapidly became a major area of reactor-based physics and one that is actively pursued at Chalk River to this day. The fundamental contributions made to this field by Bert Brockhouse and his colleagues are described elsewhere in this collection of articles.

The fission studies of John Fraser and Doug Milton were another reactor-centred activity. John was the first person to observe neutron emission from individual fission fragments and he and Doug were the first to observe the effects of shell structure in the prompt fission fragments. An interest in charged particle induced fission saw this work migrate to the MP Tandem in the early 1960's. Hans Specht developed a unique parallel-plate spark chamber detector for the Brown-Buechner spectrometer and gained notoriety as the only experimentalist who could man a one week (24 hr day) experimental run single handedly.

Research activities rapidly spread to areas only weakly related to reactor issues. One example was the mu-meson lifetime measurement of Ted Hincks. Another was the cosmic-ray neutron detector "station" developed by Hugh Carmichael's group that included Mort Bercovitch and John Steljes. This project led to an international network of stations that monitored the neutron flux at the earth's surface over several sun spot cycles. The "station" consisted of an array of BF3 gas proportional counters, each surrounded by a cylindrical plastic moderator and shielded by lead. Canadian stations were located in Deep River, Banff, Inuvik, Resolute and Goose Bay. In addition there was a trailer-housed station that was taken to various sites in the continental U.S., Mexico and Hawaii. Upon Hugh's retirement, the operation of the Canadian stations passed to Mort Bercovitch, then at NRC. The Deep River station was in operation from 1957 until 1997. Several sister stations in other countries are still operating.

Dr. Lewis' interest in a spallation-based neutron source led to a program of proton cross section measurements that involved a significant number of staff. Work was done at the McGill cyclotron (Bob Bell) and experiments were carried out at Echo Lake in Colorado (Mort Bercovitch) utilizing cosmic ray protons (the 'Deitron'). John Fraser and Doug Milton did the first Monte-Carlo calculations of the spallation neutron yield for 1 to 3 GeV protons incident on heavy elements. Their results were confirmed by an experiment carried out at the Brookhaven Cosmotron by John Fraser, John Hilborn, Ralph Green and Doug Milton, together with an Oak Ridge team. As the project progressed, it added an accelerator development component to the laboratory's activities. The studies ultimately led to the intense neutron generator (ING) proposal that went forward in the mid-1960's but failed to be funded. The Chalk River Accelerator Physics Branch was an outgrowth of this project and spallation-neutron-based reactor fuel breeding remained a field of active interest to AECL through the 1970's and 1980's.

Gamma-ray studies in the 1940's were almost always internal conversion electron studies, external conversion electron studies or, for high-energy gamma rays, electron pair studies. There were a number of lens spectrometers devoted to such studies, and there was the pair spectrometer that Kinsey and Bartholomew used in their studies of neutron capture gamma rays. (Warwick Knowles introduced curved- and flat-crystal gamma-ray diffraction spectrometers to the laboratory and led the world in precision gamma-ray measurements in the following decades. He carried his innovative research into many other ventures). Bob Bell and Bob Graham used a double-thin-lens spectrometer set-up to select cascade radiations and determined the intermediate-state lifetime using their nanosecond lifetime measurement technique.

Lloyd Elliott, who led these activities, recognized the potential of a much higher resolution spectrometer for internal conversion electron studies and initiated a program to develop such a device. Joe Wolfson did the initial studies, with the leadership subsequently passing to Bob Graham. Preliminary work led to the choice of the iron-free $\pi\sqrt{2}$ design with a three-coil-pair arrangement to create the magnetic field. Graham Lee-Whiting played a pivotal role in accurately calculating the coil parameters required to provide the magnetic field shape needed to achieve the performance promised by the $\pi\sqrt{2}$ spectrometer design. Subsequent tests of the instrument constructed by the team of Bob Graham, George Ewan and Jim Geiger showed it to meet the design criteria. The resolution of a few parts per thousand that characterized most studies allowed resolution of the L subshell conversion line components and gave accurate information on transition multipolarities as well as energies. In addition to this nuclear-type information, studies done with the spectrometer provided information on atomic phenomena including atomic level widths, Auger-electron spectra, and L subshell fluorescent yields; these last studies being led by Ian Campbell of the University of Guelph. The instrument was primarily a point-by-point measuring device and it required high-specific-activity source material if high resolution was to be realized. The advent of the high-resolution germanium detector and the shift in interest from studies of reactor-produced activities to accelerator-based studies resulted in the instrument seeing little service for many years. However, in the early 1980's, it was used for the 17 keV neutrino studies of Don Hetherington, Bob Graham, Aslam Lone, Jim Geiger and Graham Lee-Whiting. Several laboratories built scaled-down copies of this 1 metre radius instrument.

One of the experimental facilities planned for the EN Tandem installation was a large scattering chamber to be used for charged particle reaction studies. The assumption was that the particle detectors would be scintillation counters. This was in the mid 1950's and Allan Bromley was encouraging I.L.(Dick) Fowler to get the counter development group involved in the development of solid-state charged-particle detectors. Jim McKenzie, a postdoc in the group, took up the challenge and produced such detectors. This initiative had implications. One was that a large scattering chamber that had been built for charged particle reaction studies using scintillation counters stood unused for many years and finally disappeared. Another consequence of major importance was the fact that this work led to the involvement of the counter group in Li-drifted germanium, Ge(Li) detector manufacture. Alister Tavendale developed techniques for making large volume detectors. George Ewan worked with him in applying these novel devices to a large variety of physics problems and demonstrating that they would have a profound impact in improving and simplifying high-resolution gamma-ray studies. Adoption of these detectors by scientists in all areas of potential application was limited only by their availability.

Work with the EN Tandem Accelerator led to major contributions to our understanding of the atomic nucleus. Especially interesting were the experimental and the theoretical discoveries that increased our understanding of the s-d shell nuclei, i.e. the nuclei from ^{16}O to ^{40}Ca. The high resolution and variable energy of the Tandem Van de Graaff beams and the state-of-the-art detectors available for measuring the reaction products, were well suited to studies of nuclei in this region of the periodic table. Also theoretical physicists had reached the stage in shell model calculation where realistic modelling for these nuclei was practical and unique predictions could be made of experimentally measurable nuclear properties.

Harry Gove headed the accelerator-based Nuclear Physics group during a remarkable period in the 1950's that was exceedingly productive. Ted Litherland, John Ferguson and Harry Gove discovered collective-like excitations in light nuclei that closely resembled those described for heavy nuclei in the famous 1953 paper by Bohr and Mottelson. During the same period, Einar Almqvist, Allan Bromley and John Kuehner discovered that energetic collisions between two ^{12}C nuclei sometimes formed states of ^{24}Mg that had the characteristics expected for a nuclear molecule; an unexpected collective behaviour that was described to the media of the day as "kissing nuclei ".

Fig. 1 Chalk River physicists (left to right) John Kuehner, Allan Bromley and Einar Almqvist in the experiment control room of the 3MV vertical Van de Graaff accelerator. The year is 1957 and in the background, on the right, can be seen relay racks each containing six channels of a Moody kicksorter (so called after its designer).

This was the beginning of the study of nuclear reactions with precision beams of heavy ions. Ted Litherland and John Ferguson developed their famous alignment techniques, Method I and Method II, for measuring angular correlations of gamma rays from states formed in nuclear reactions. Bill Sharp provided theoretical guidance for this development and he and Jim Kennedy calculated the coefficients needed to interpret these correlations. This work revolutionized the determination of spins and was quickly adopted by other laboratories. This group of physicists made many exciting discoveries with the EN Tandem and were world leaders in nuclear structure research.

These early EN Tandem studies had a major impact when presented at the International Nuclear Physics conference held at Queen's University in 1960, under the joint sponsorship of AECL and Queen's. A further noted feature of this conference was the speed with which the Proceedings appeared under the joint editorship of Allan Bromley and Erich Vogt. Erich's recollection of this exciting time is: "The hard-cover volume of over 1000 pages was mailed to the conference participants four weeks after the conference. Every page was retyped either from rough manuscripts or from transcribed recordings of talks and discussions at the conference. All the drawings and figures were redrawn. The typing, redrawing and paste-up of the manuscripts were done in two weeks at CRNL by a team of about 20 typists (including Marilyn Buyers) working round the clock with the editors. The University of Toronto Press went from the paste-up to the bound volume in the following two weeks. All of this was done in an era before participants came to conferences with photo-ready copies of their talks. This is one of the few conference proceedings that have ever recognized the fact that such proceedings decay with a half-life of several months and therefore the period for their emergence should be weeks, not months."

In the early 1960's, Allan Bromley, and later, Harry Gove left Chalk River to lead MP Tandem Accelerator nuclear research projects at Yale University and at the University of Rochester respectively. They left a few years before the replacement of the EN Tandem at Chalk River with the more powerful 10 MV MP Tandem machine. The EN Tandem was moved to the University of Montreal, where it is still in use. Geoff Hanna, the branch head, skillfully oversaw the procurement and installation of the new MP Accelerator in a facility with expanded machine, target, and control rooms. Later, Lloyd Elliott became Head of Research, Geoff Hanna became Director of Physics, and Doug Milton became Head of the Nuclear Physics Branch. Over a short period, around 1967-8, the Tandem Accelerator nuclear group dispersed to the expanding university laboratories; Ted Litherland to the University of Toronto, John Kuehner and Phil Ashbaugh, the head of Tandem Operations, to McMaster University and Robin Ollerhead to the University of Guelph. Einar Almqvist, who added such strength to the group, sadly passed away. John Ferguson, the senior member, Cyril Broude, who later left to go to the Weizmann Institute, and Tom Alexander, who had joined in 1964, remained, bolstered for a period by postdocs and visitors, including Otto Hausser, John Sharpey-Schafer, Brian Hooton, Dietrich Pelte, and Finn Ingebretsen.

Otto Hausser stayed and initiated a series of brilliant experiments to measure quadrupole and magnetic moments of nuclei using the new heavy-ion beams available from the MP Tandem. The reorientation effect in Coulomb excitation, hyper-fine interactions in highly stripped ions, pulsed beams, and liquid-metal targets mounted in magnetic fields, were a few of the challenging experimental techniques he mastered in this quest. Later, this would lead to Otto achieving beautiful discoveries relating to the mesonic effects in the structure of nuclei in a collaboration that included David Ward, Faqir Khanna and Ian Towner. Otto went on to an outstanding career at Simon Fraser University and TRIUMF in 1983.

A merging of groups occurred during the mid- to late-1960's. Bob Graham, Jim Geiger and George Ewan complemented their research into the precision spectroscopy of heavy nuclei with studies of heavy-ion induced reactions, especially (HI,xn) reactions, using the newly won power of Ge(Li) gamma-ray detectors. They were joined by David Ward and later by Bob Andrews and John Hardy. At about the same time, Gordon Ball, Walter Davies, Jim Forster and, later, Art McDonald came to the MP Tandem group and brought it back to full strength and ability. It wasn't long before Doug Milton had the MP Tandem upgraded to 13MV on the terminal, and enhanced the laboratory considerably with the addition of powerful data analysis computers. New computers eventually replaced the PDP1 computer with which Chalk River had pioneered computer-based data acquisition in an accelerator laboratory. A target preparation laboratory was established, along with an experiment preparation area. A Q3D magnetic spectrometer and the on-line isotope separator were added to the experimental facilities. The sense of pride that pervaded the Tandem laboratory was an affirmation of the inspired scientific leadership of Doug Milton and Geoff Hanna.

Strong collaborations existed with researchers from Queen's University including Hugh Evans, George Ewan, Bern Sargent, Bill McLatchie, Hay-Boon Mak, Hamish Leslie, Peter Skensved and others, and with Ted Litherland and his students, including Bill Diamond, from the University of Toronto. These were later to expand to include physicists from Laval, the University of Montreal, McMaster and Manitoba. About 1970, a collaboration, including Tom Alexander, Otto Hausser, John Ferguson and Art McDonald from CRNL, and Ted Litherland and Bill Diamond from the University of Toronto, carried out a landmark study of the E2 transition rates and alpha-particle widths for the decay of the ground-state band of ^{20}Ne.
Daniel Disdier from Strasbourg, an exchange visitor, and I.M. Szoghy from Laval University contributed to the alpha scattering experiments. The experiments showed that the shell-model predictions of Malcolm Harvey described the nature of this nucleus even to the many collective-like features that were measured. The experiments, combined with the calculations of Malcolm Harvey, Ian Towner, Faqir Khanna, Paul Lee, and Ron Cusson, clearly showed that the ^{20}Ne band effectively truncated at spin 8^+, a fact predicted by the SU_3 shell model, but not the collective model. The theoretical calculations indicated that the possible 10^+ level of the structure was pushed to much higher energies and effectively

separated from the "band". This series of experiments used the powerful methods of nuclear research that had been pioneered and developed at CRNL over many years: radiative capture and the Doppler-shift attenuation methods to measure gamma-radiation widths, and resonance scattering to measure alpha-particle widths. The radiative capture experiment was the key experiment carried out with the differentially-pumped ^{4}He target and benefited considerably from improvements made to that system by Bill Diamond. John Ferguson, an expert in all aspects of these types of experiments, automated the resonance searches to make the experiments very enjoyable. There was a marvellous "resonance" of people and talent in this venture.

The Doppler-shift attenuation method had a particularly interesting history at CRNL. As early as 1948, Lloyd Elliott and Bob Bell discovered and used this method to measure the lifetime of the first excited state of moving ^{7}Li nuclei created in solid material by irradiating ^{10}B with neutrons from the NRX reactor. The method was quickly adapted to accelerator-based experiments. Later, the power of the method was greatly enhanced by Ted Litherland and his collaborators when they used heavy-ion beams and light targets to achieve high recoil velocities of the excited nuclei, and NaI(Tl) gamma scintillation counters as detectors. In ~1963, when the high resolution Ge(Li) detectors developed at CRNL by George Ewan, Ivan Fowler, and Alister Tavendale became available, the method became even more powerful. It was quickly applied by Ted Litherland and Cyril Broude. The high resolution of the Ge(Li) detectors allowed easy observation of the Doppler broadening of the gamma rays which gave line shapes characteristic of the recoiling ion, stopping medium and the mean lifetimes of the decaying nuclear states. The newly developed data acquisition systems, employing transistorized ADC's with large dynamic range and computers with enhanced memories, became available just in time to allow full advantage to be taken of the increased resolution of the new detectors. These devices were first supplied by the Electronics group, and later by commercial suppliers and by strong CRNL technical groups. Bruce Winterbon made important contributions to the analysis of these experiments through his theoretical work on stopping powers.

Following a suggestion from Ted Litherland in the summer of 1964, Ken Allen and Tom Alexander developed a new way of applying the recoil-distance method called the "plunger" method for measurement of lifetimes in the 10^{-10} to 10^{-12} second range.
Ken Allen was a summer visitor from Oxford, who knew his way around CRNL from his work there in the early days when the group was headed by Bern Sargent, and accomplished much during that summer. Geoff Hanna and Lloyd Elliott quickly knew of the plunger development and immediately assimilated the details and contributed with their knowledge and encouragement. Dr. Keys, the scientific advisor to the president of AECL, also soon knew, as he was a regular visitor to the EN Tandem laboratory. The plunger method took advantage of the high resolution of the Ge(Li) detectors to measure directly the decay curves of short-lived excited levels of nuclei traversing a small distance between a target foil and a thicker metal stopper foil. This technique bridged the gap in experimental methods between direct electronic timing methods and the Doppler-shift attenuation method and made possible direct and accurate measurement of the E3 transition in ^{16}O and other light nuclei. Joe Gallant, who became famous for his abilities to make targets for accelerator experiments, later, about 1969, devised a method to produce the exceptionally flat targets necessary for application of the method to shorter lifetimes and heavier nuclei.

The study of hyperfine interactions in stripped ions was a very interesting topic that was hotly pursued in the 1970's. One Tandem group, including Bob Andrews, Jim Geiger, Bob Graham, David Ward, Otto Häusser, and their collaborators, studied not only the transient but also the static fields created by the electrons remaining on the nucleus of a partially stripped ion. This was done by studying the time dependence of perturbed angular correlations of the gamma rays from nuclei formed in heavy-ion-beam-induced reactions and allowed to recoil into gas or vacuum. The plunger apparatus was used in some studies since the effect of the interactions could be "switched off" after a controlled period of time by the ions entering the stopper. The enormous fields created at the nucleus allowed magnetic moments of short-lived levels to be determined as never before.

As these developments occurred, there was an explosion in the number of lifetimes measured in nuclear-structure laboratories in Canada and around the world. However, Canada maintained a lead due not only to its excellent detectors but also the improved accuracy and breadth of the stopping power data, vital to the Doppler-shift attenuation method, at its disposal. A systematic investigation of stopping powers by a group, including Bob Andrews, Gordon Ball, Walter Davies, Jim Forster, Ian Mitchell and David Ward, significantly improved the accuracy of lifetime measurements. They were also to develop light-ion implanted metal target foils suitable for better exploiting the use of inverse-reactions (a heavy-ion beam accelerated onto a light- nucleus target) to produce nuclei recoiling at high velocity where the stopping powers were accurately known from their measurements. The stopping power data were intrinsically interesting aside from their use to nuclear experimenters, offering new insights into the physics and material-sciences research of Ian Mitchell and Bruce Winterbon.

During Dr. Lewis' reign, a Future Systems Working Party concerned itself with potential new AECL initiatives. Subsequent to his retirement, some of these activities were taken on by a Physics Advanced Systems Study (PASS) committee chaired for many years by Gil Bartholomew. One of the major studies of this committee concerned laser fusion, which is seen as a potential neutron source for reactor fuel breeding. An important component of this study were trips to Livermore and Los Alamos led by Arthur Ward. The director of the laser fusion, research program at Livermore, when asked what he felt could be achieved with a $5M per year program, replied that, for that money, he would be willing to send a postcard every week informing AECL of the progress being made in laser-induced fusion. AECL chose to restrict its activities to a watching brief, led for many years by Jim Geiger.

Shortly after coming on staff, John Hardy initiated the construction of an on-line isotope separator and built up a "nuclei far from stability " research group that included Vern Koslowsky, Erik Hagberg, Hermann Schmeing and, latterly, Guy Savard. The group established collaborative ties with the Queen's group, Dick Azuma at the University of Toronto, and Harry Duckworth's (later Bob Barber's) group at the University of Manitoba. The isotope separator was an unusually high resolution type ideally suited to precision measurements. Extensive work was done on the development of techniques for the He-jet transport of short lived radioactive species from a production target to the ISOL ion source. The coupled system was capable of delivering analysed beams of refractory elements with half-lives as short as 100 ms. A very fast tape transport system was developed to rapidly transport mass separated product from the ISOL focal plane, or the He-jet nozzle, to a radiation detector station. Studies included the level schemes of nuclei far from stability, delayed proton and alpha decays, nuclear mass measurements, and the weak interaction; most notably superallowed beta decay, where measurements of outstanding accuracy were performed. This work had the benefit of a strong collaboration, on the theory side, with Ian Towner. The group's work provides our current best value for the V_{ud} element of the Kobayashi-Maskawa matrix.

Malcolm Harvey, Faqir Khanna, Paul Lee, Ian Towner, and their collaborators were very interested in the rapid developments occurring in particle physics from 1970 on. Their primary interest was in understanding the role the quark structure of the nucleons played in determining the structure of the nucleus.

In 1974 Dave Earle and Art McDonald dealt remarkably quickly with a claim that a two-photon decay mode had been observed in addition to the single 2.2 MeV gamma decay associated with the radiative capture of n+p. They set an upper limit of $5*10^{-6}$ for the two photon branch. Later in their careers Dave became a participant in the SNO project with major responsibilities relating to the heavy water vessel and Art, then at Queen's University, became SNO Director.

Consideration was given to the addition of a post-accelerator in the early 1970's, and it was these discussions that prompted Bruce Bigham and Harvey Schneider to come up with their proposal for a superconducting cyclotron. The Accelerator Physics Branch went on to develop the concept, test a full scale superconducting magnet, and later to construct the cyclotron for the TASCC facility.

About 1980 David Ward proposed the building of a large 4π array of Compton-suppressed germanium gamma-ray detectors to support the studies on high-spin states in nuclei. Bob Andrews and Otto Hausser were collaborators in the conceptual phase and Vern Koslowsky and Hermann Schmeing, who became intrigued by the discussions of possible designs for the instrument, came up with the geometric design that was adopted.

The timing roughly coincided with the start of construction of the superconducting cyclotron facility. With the passage of time the accelerator-based work had become a dominant portion of the basic research at AECL, and university collaborations played an important role in these activities. The nuclear physics research was seen increasingly as a "National Laboratory" function. Despite increasingly stretched financial resources, AECL found the funds to support the addition of a superconducting cyclotron post accelerator to the tandem accelerator facility, but indicated that staff would have to look elsewhere for funds for major experimental equipment.
David Ward and Bob Andrews established a collaboration with Jim Waddington of McMaster University and Paul Taras of the University of Montreal to seek the major portion of the funding for this "8π spectrometer" from NSERC. Their efforts were successful, and the instrument they designed and built proved to be the pre-eminent instrument in the field for a decade or more and attracted scientists from both the USA and Europe to the laboratory as users. David Radford joined the group, bringing unique expertise in computerized analysis of the spectrometer data, and Gordon Ball became active in the group.

Fig. 2 This 1987 photograph shows the 8π spectrometer at the temporary location it occupied in Target Room 2 prior to the funding of Phase 2 (completion of work on two new target rooms and installation of the beam lines) of the TASCC project. Paul Taras (University of Montreal) is seated at the data acquisition computer terminal and David Radford is looking into the oscilloscope on the left. David Ward (left) is touching the spectrometer, open for target inspection, with Xuan Tran, a technologist from McMaster University, looking on.

Many experiments could be carried out with relatively modest manpower requirements and the group, together with their many visitors, were able to effectively use large blocks of accelerator beam time. Victor Janzen contributed to the work, first as a postdoc and later as a staff member. Angular momentum coupling and superdeformation were areas of concentrated investigation. Alfredo Galindo-Uribarri, who did an important part of his thesis work on the 8π when a graduate student of Tom Drake at the University of Toronto, developed a particle detector mini-ball that fitted into the ample 8π target chamber cavity and permitted particle-gamma coincidence measurements. Experiments by Alfredo provided the first evidence for hyper-deformed rotational states in rare-earth nuclei.

Dag Horn worked closely with René Roy and Claude St. Pierre of Laval University and Tom Drake in establishing a charged-particle reaction-mechanisms program at the TASCC facility. David Bowman later came on board to support these activities. This program was blessed with, and provided the training ground for, a large number of Laval University graduate students.

A ^{14}C dating program was started under Bob Andrew's initiative and had Doug Milton, Walter Davies, Vern Koslowsky, Barrie Greiner, Yoshio Imahori and Gordon Ball, with Jack Cornett, Gwen Milton and Bob Brown from the Environmental Research Branch, as participants. In its later stages, the program expanded to include ^{36}Cl and ^{129}I studies. In the course of the ^{14}C studies it became apparent that the ^{14}C levels at the Chalk River site were considerably above normal, and further study led to enhanced understanding of the production and migration of this reactor product. The ^{129}I dating proved to be a technique applicable to nuclear non-proliferation safeguards work. In addition, the surprising result that ^{36}Cl was present in spent fuel in significant amounts, and in the long term would become one of the dominant activities, was revealed.

Jim Forster led a program that applied ion channeling techniques to fission lifetime measurements and materials analysis, with superconducting material being a focus of interest in the final years.

In 1986 AECL underwent a major reorganization, with Doug Milton assuming the position of Vice President Research and TASCC becoming a Division, with two branches, under John Hardy. The Operations group became the TASCC A&D branch under Neil Burn, later Hermann Schmeing, and briefly under Bill Diamond. Nuclear Physics under Jim Geiger formed the other branch. In keeping with its "National Laboratory" role, the laboratory instituted External Program Reviews and a TASCC staff position was established at McMaster University and filled by Stephane Flibotte. In order to defray some of the operating expenses of the facility, staff sought out clients who would purchase beam time on the facility at commercial rates and provided support to these clients during their runs. Jim Forster and Bob Andrews were major players in this activity.

The last major TASCC initiative was the ISOL group's Penning trap proposal championed by Guy Savard and carried forward as a collaboration with Kumar Sharma and Bob Barber of the University of Manitoba and John Crawford, Johnathan Lee, and Bob Moore of McGill. While construction and installation of this facility were completed before the TASCC closing, commissioning was not.

In the mid-1990's AECL found itself facing a serious financial crunch. Several research programs were cut, and the neutron scattering and TASCC programs were forced to seek alternative government funding to support their operation. John Hardy made a valiant effort to gain this support for the TASCC programs but was ultimately unsuccessful, and the TASCC laboratory was closed in 1997. (The neutron scattering program transferred from AECL to NRC under an interim three year funding arrangement.) Of the major pieces of experimental equipment, the 8π spectrometer went to the Lawrence Berkeley Laboratory and is just now on its way to ISAC (the new radioactive beam facility at TRIUMF), the Penning trap is now at the Argonne National Laboratory, and the charged particle detector array is at Texas A&M University. In each case they continue to be used by the university consortia that championed their construction. The particle group's earlier detector array has gone to the National Accelerator Centre in South Africa. Some components of the on-line separator went to ISAC and some Tandem ion-source components to the University of Toronto.

Perhaps the most important contribution that the basic research made to AECL was its role in providing AECL with a high international profile. Chalk River placed Canada on the map as far as nuclear research is concerned. Many of the Canadians currently active in subatomic physics had their initiation at Chalk River. Above all, the work at Chalk River demonstrated that a small country can, with a dedicated effort, be at the top of the world in excellence in research and development. The spirit that encouraged and brought out the best a young researcher could achieve, started in the first days of the laboratory, was very much alive in the TASCC Division well into the 1990's. The challenge to future generations is to match or surpass the Chalk River achievements. The memory of the glory days of Chalk River will remain with those who were privileged to play a role in the laboratory's activities.

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This article is limited to activities that the authors felt competent to cover; it is not intended to be a comprehensive history. We apologize for any omissions. We appreciate the work of former colleagues in reviewing the draft article.
Some material was extracted from a manuscript by Faqir Khanna.

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