THE NATIONAL RESEARCH COUNCIL'S IMPACT ON CANADIAN PHYSICS

by Paul A. Redhead

In 1916 the Honorary Advisory Council on Scientific and Industrial Research was created by the Canadian government; this group was known by its short title of National Research Council. Of the eleven members of the first Council, eight were academics (one a physicist, J.C. McLennan), three were from industry, and one was a banker [1,2]. The difficulties in 1917 were summarized later by C.J. Mackenzie, "the NRC was instructed to coordinate and promote scientific and industrial research in Canada. The NRC soon found there was little or nothing to coordinate." [3] Only thirty-seven companies in Canada had research laboratories and most were staffed by one man. Fewer than a dozen Ph.D.s in pure science had ever been granted in Canada. It was estimated that there were only about 50 researchers in pure science in Canada.

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A program of grants to universities for the support of research was started in 1918, though it proved difficult to spend the $70,000 allocated; in 1918-1919 only $10,301.39 could be expended on five projects. One of these projects was in the area of applied physics, "an investigation on the action of ultra-violet rays in certain industrial applications" at L'École Polytechnique. By 1939 there were 26 research grants, about one-third being in physics.

Four NRC Studentships and three Fellowships were granted in 1918 at the universities of Toronto, McGill, Alberta, and Saskatchewan. NRC had recognized that the limited number of researchers in Canadian universities and industry was a major barrier to the development of an industrialized country and that an expansion of postgraduate training was required. The NRC scholarship programs were to prove an effective solution in the long run. The growth of the Awards program was slow because of the lack of adequate research facilities in Canadian universities and, as a result, many candidates asked to be allowed to apply to American universities. By 1926, however, 155 students had completed post graduate studies in science in Canada, with NRC support, and, of these, 123 were actively engaged in research in Canada. Several outstanding physicists were amongst this group, including Gordon Shrum and Don Rose. The Scholarship program grew from $5,500 in 1918 to $15,675 in 1937.

Prior to 1929 almost all Canadian physics was published in foreign journals. In 1929, NRC started the Canadian Journal of Research (CJR) which provided a place for the publication of the results of physics research in Canada; later the CJR was subdivided and the Canadian Journal of Physics (CJP) begun.

NRC began research in its own laboratories in 1925 in rented space in Ottawa; the new Sussex Drive laboratories of NRC were opened seven years later, in 1932. In 1928 the first full-time President was appointed: he was H.M Tory, a physicist from the University of Alberta. By 1929 there were 598 people working at NRC but only 105 of them were paid. In 1929 the NRC laboratories were reorganized into four Divisions, one of which was the Division of Physics and Engineering under its first Director, Robert W. Boyle, also from the University of Alberta. By 1931 the Division consisted of 8 professionals; as later events would prove they were a remarkable group - B.G. Ballard, G.S. Field, J.J. Green, G. Klein, G.C. Laurence, C.D. Niven, D.C. Rose, and

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K.F. Tupper. In 1936 the mechanical and aeronautical engineers were split off and the Division's title became the Division of Physics and Electrical Engineering; in 1947 the electrical and electronic engineers were separated so the title became the Division of Physics.

The activities of NRC during the thirties were severely restricted by the Depression. For example, the total budget of NRC dropped from $550,334 in 1930-1 to $379,499 in 1933-34. The Division of Physics expanded slowly until the outbreak of the war in 1939, by which time there was a staff of 26 physicists and electrical engineers and 37 technicians. The research prior to 1935 was almost entirely nonmilitary and of an applied nature related to industrial problems. The type of research is indicated by the names of the research sections -- Acoustics and Ultrasonics [George Field], Electrical Engineering [Guy Ballard], Electrical Measurements [A.J. Grant], Heat [Charles Niven], General Physics [Don Rose], Light [Leslie Howlett], Metrology [R.H. Field] which was transferred to NRC in 1931 from the Department of the Interior, Radio [John T. Henderson], Radiology [George Laurence]. Heat, Light, Sound, and Electricity were the backbone of physics text books in the 1930's, so the sectional arrangements were conventional. The General Physics section, which consisted of Don Rose only, was the place for those important problems that did not fit neatly into the usual pigeonholes. Much of the work of the Physics Division was designed to meet the requirements contained in the NRC act: "The investigation and determination of the standards and methods of measurements, including length, volume, weight, mass, capacity, time, heat, light, electricity, magnetism ... physical constants ...The standardization and certification of ... scientific and technical apparatus and instruments for government service." This role was very similar to that of the National Physical Laboratory of the UK. A detailed description of the work of the Division of Physics from 1929 to 1952 can be found in W.E.K. Middleton's history of the Division [4].

In 1935, Prime Minister R.B. Bennett was feuding with Tory, who had been appointed President of NRC by Mackenzie King; he replaced Tory with Major-General A.G.L. McNaughton, the Chief of the General Staff. McNaughton was sympathetic to the Conservative party but was a handicap to the Bennett government because of the turmoil he had caused by his management of relief camps during the Depression. " If you think, Andy," Bennett declared, "that I am going to face an election with you as Chief of the General Staff, you'd better think again. From now on I address you as President of the National Research Council" [5]

McNaughton did not drastically alter the course of research at NRC but he did increase the efforts devoted to urgent projects needed to improve Canada's military position. This slowly increasing military-related R/D from 1935 to 1939 led to the dramatic expansion of the applied scientific and engineering effort in World War II. During the four years of McNaughton's term as President, the budget of NRC was increased by 80%, although this was still miserly. In 1939 NRC had a paid staff of 300 and a budget of 1 M$.

In the autumn of 1937 McNaughton began to discuss with the Department of National Defence the possibilities of detecting aircraft by radio methods. In the spring of 1939 the British government decided to inform the Dominions, in strict secrecy, of the progress made in the UK in developing radar. J.T. Henderson, head of the Radio Section of the Division of Physics, was chosen as the scientific representative of Canada at the meetings in the UK to demonstrate radar in March 1939. Henderson had worked on the development of the cathode-ray direction finder since 1936, making him particularly suited to this liaison task. On his return to Canada in June 1939 he wrote a detailed report on the state of radar development in the UK. The Canadian Chiefs of Staff were impressed with the possibilities of radar but the requests for additional finances were ignored by the government. The Radio Section was to become the Radio Branch and during the war became larger than the rest of the Physics Division.

Five days after September 10th 1939, when Canada declared war on Germany, the NRC Council appointed C.J. Mackenzie as acting President of NRC, in the absence of McNaughton who assumed the position of Officer Commanding the First Canadian Division.

PHYSICISTS AT WAR: 1939-1945

The history of NRC's activities during the war have been described by Eggleston [6]. The wartime activities of the Division of Physics [4,7] and its Radio Branch [8,9] have been reported in some detail; space will only permit brief mention of the major projects in physics. It has been said that the first world war was a chemist's war and the second world war was a physicist's war; it is certainly true that in the second world war physicists in Canada were central to wartime R/D and that NRC took the lead.

Throughout the war Mackenzie (as acting President) was a punctilious letter-writer in keeping McNaughton informed of NRC activities; these letters give an insight into the wartime activities of NRC [10].

The Radio Section at the start of the war was grossly underfunded and understaffed to tackle the development of radar. In September 1939 the staff consisted of J.T. Henderson, D.W.R. McKinley, F.H. Sanders and H.R. Smyth, and eight technicians; by March 1940 the number had grown to twenty-two. Little financial help came from the government until the fall of France in 1940. In August and September the Tizard Commission [11] came to Canada and the United States, resulting in one of the most important scientific developments of the war. The Commission, named for its chairman Sir Henry Tizard, brought to the Canadian and the U.S. governments the most important British secrets of military science including the cavity magnetron and the proximity fuze amongst much else. One effect of the Tizard Commission was to persuade the governments of Canada and the U.S. to mount massive programs to develop radar, and particularly microwave radar. Colonel (later Brigadier) F.C. Wallace of the Tizard Commission remained behind in Canada and, in due course, was put in charge of the Radio Branch. Resources now became available to NRC, in the first instance from a group of patriotic business men who moved faster than a lethargic government, to expand radar development and other military R/D. The Radio Branch expanded rapidly reaching a total staff of about 300 by war's end. Radar equipment was developed for the three Canadian services and the British government; a plant to manufacture radar and optical equipment, called Research Enterprises Ltd., was set up in Toronto.

Another project related to radar was the development of the proximity fuze (an electronic fuze for shells operated by radio waves reflected from the target) which was brought to Canada by the Tizard Commission. The project was operated by the University of Toronto and was funded by NRC and the university. The project started in September 1939 and, in April 1943, the engineering staff was reassigned to work with groups in the U.K. and U.S. All proximity fuzes were manufactured in the U.S.

In March of 1940 George C. Laurence started construction of a nuclear pile in the Sussex Street laboratories of NRC, in great secrecy, using half a ton of uranium oxide and ten tons of calcined coke (used for making graphite) [12]. Although the pile was unsuccessful because the materials were not sufficiently pure, it allowed Laurence to become familiar with the nuclear programs in the U.S. and U.K. In September 1942 the Canadian and U.K. governments agreed to a joint nuclear laboratory in Montreal administered by the NRC. The first director was H.H. Halban who had been in charge of slow neutron research at Cambridge University; he arrived in late 1942 and the first group of British scientists arrived in January 1943. Staff was recruited from several Canadian universities to provide the core of the Canadian group at Montreal. The combined staff grew to 340 by the end of the year and was housed in the new buildings at the University of Montreal. In early 1944 an agreement with the U.S. government for a joint program of research between the University of Chicago and the Montreal project was signed. The moderator of the planned pile was to be heavy water which was being produced in a plant at Trail, B.C. A site for the project was rapidly constructed at Chalk River, Ontario, and John Cockroft was appointed Director in Charge. On September 5th, 1945 the first nuclear reactor in Canada (ZEEP) went operational at Chalk River. When the laboratories and town (Deep River) neared completion, the management was taken over completely by NRC. David Keys of McGill was appointed Vice President and W.B. Lewis was appointed Director of Research, replacing Cockcroft who returned to England to head the atomic energy project there.

The Optics section designed and helped to staff the optical component factory at Research Enterprises Ltd. which was set up in 1940 to provide Canada with an optics industry to manufacture optical glass and instruments for military purposes. The section established a small optical workshop in the Ottawa laboratories to train optical mechanics and to construct experimental optical equipment. By 1944 the staff of the section had grown to 44.

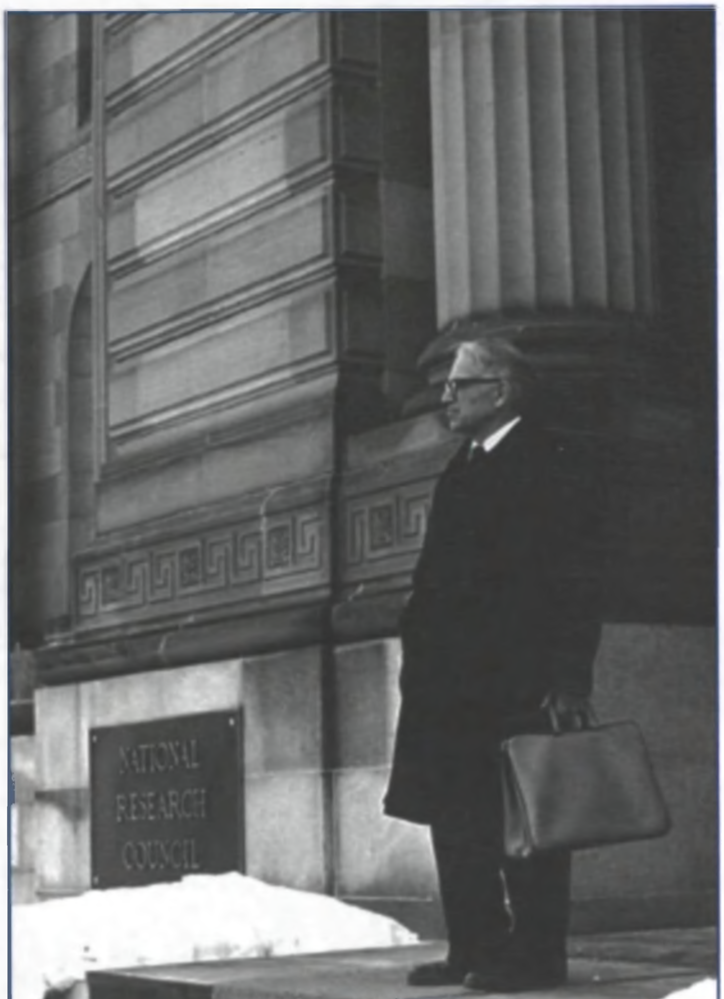
The rest of the Division was involved in many other projects in applied physics for the war effort, these included work on ASDIC and problems of defense against acoustic torpedoes, the degaussing of ships, and studies of the properties of ice in connection with the Habbakuk [13] project, amongst a multitude of smaller projects for the Canadian services and the British government.

The work on radar, nuclear energy, optics, and other applied physics projects during the war had a profound impact on the establishment of the Canadian high-technology industry after the war, by training a cadre of experts and by involving several universities in research in applied physics. Perhaps the biggest impact was on national confidence by demonstrating that Canada, with an economy based mainly on natural resources before the war, was capable of developing a high technology industry and research infrastructure. The effect on NRC was to establish its role as the national laboratory for Canada, the provider of funds for research in universities and industry, and an advisor to government on science. It also generated a growing confidence within NRC of its own ability and international stature.

GROWTH AFTER THE WAR: 1945-1975

During this period the principal objectives of NRC were to promote research at Canadian universities, to build up research capabilities in Canadian industry, and to raise the calibre of research at its own laboratories to world class. The activities of NRC during the war provided a new credibility for NRC, and science in general, in the eyes of the government. This resulted in increased government funding and led to a period of scientific self-government with a minimum of governmental interference (later called by some the Golden Age). From 1962 onwards, NRC's power to control overall science policies decreased as a result of the Glassco Commission's inquiry into the organization of research and development activities in the federal government [14] and culminated in the Lamontagne reports at the end of the decade [15]. These reports were highly critical of NRC and resulted in much closer control by the government of science policies and funding. The politicization of basic science that occurred in the 1960's has been studied in detail by Louise Dandurand [16].

In 1966 the newly created Science Secretariat proposed "a comprehensive review of physics research in Canada and ... assessing future needs." [17] The Canadian Association of Physicists appointed a steering committee to undertake the study, which was chaired by D.C. Rose who had just retired from the Physics Division at NRC. This report had a considerable influence on the subsequent debates on the financial and procedural choices to be made in physics research.



The picture of Herzberg standing on the NRC steps, gazing out confidently should be burnished in the memory of every Canadian physicist. It represents what was finest about our past century.

Reorganizing After the War

At the end of the war many members of the Physics Division left for positions in universities and industry and most of the Americans, who had joined NRC before the U.S.A. was in the war, returned to the U.S.A. During 1946 the staff of the Radio Branch decreased to 210 and the rest of the Division of Physics to 97. In 1947 the Radio Branch was separated from the Physics Division to form a new Division of Radio and Electrical Engineering.

With the arrival of Gerhard Herzberg in the Physics Division in 1948, physics at the NRC was given new impetus, one that would have an impact well beyond the NRC laboratories. Herzberg became Director of the Division in 1949, on the retirement of Boyle, and he set out to create a world class laboratory that would attract the best scientists from Canada and abroad. By the 1950's the Physics Division consisted of groups in several fields whose research ranged from basic to very applied. In all cases, Herzberg's emphasis was on excellence in research, and on creating an environment that was conducive to creative research.

Grants, Graduate Scholarships, and University Interactions

In 1949 NRC started the Post-doctorate Fellowship Program which selected recent graduates to work for a few years (typically two) in the NRC laboratories. Over the years many bright young Post-doctoral fellows were attracted to the Physics Division, both from Canada and abroad. Not only did this keep new blood flowing through the NRC laboratories but it also created a pool of highly qualified young physicists, many of whom were hired by Canadian universities. Later the PDF program was extended to include fellowships held at Canadian and foreign universities. This program proved to be extremely successful, not only for physics but for Canadian science generally.

As well as PDFs, university professors were also encouraged to spend time in the NRC laboratories, either during the summer months or on sabbatical leave. While in Ottawa the scientists had use of the NRC facilities and often developed long term collaborative programs with NRC scientists. Many undergraduate physics students also spent their summers at the NRC .

During the 1950's there was important research being done in the physics departments of Canadian universities, and it was part of the NRC mandate to encourage and support this work. The Grants and Scholarships program was largely responsible for the rapid increase in physics research at Canadian universities during the 1950's and 60's. In the twenty year period from 1946 to 1966 the grants and scholarship budget grew from about 0.28 M$ to 34 M$. Proposals for research support were usually submitted by individual scientists, and grants were awarded on the basis of recommendations from peer review committees.

The staff of the Physics Division played a direct role in establishing programs, both in teaching and research, at Canadian universities. In 1954 D.K.C. MacDonald, while full time on the staff of the NRC, was Chairman of the fledgling Physics Department at the University of Ottawa and built up the department over the next five years. In a similar vein, E.P. Hincks, in 1965, took a partial leave of absence from the NRC to head the Physics Department at Carleton University, while at the same time remaining head of the NRC Particle Physics Group. Before returning full time to the NRC in 1975, Hincks set up a new program at the university to study the physics of particle detection. Within a few years particle detection systems, developed as a result of this work, were in operation at major laboratories in North America and Europe.

Other staff of the Physics Division were also involved in organizing and supporting research programs with the university community. For instance, a collaborative program involving a cosmic ray station on Sulphur Mountain in Alberta was established with the University of Calgary. In another case, funding was obtained for satellite (ISIS) instruments, developed at the University of Calgary and York University, which produced the first images of the aurora from space.

During the presidency of E.W.R. Steacie[18] the expenditures by NRC on grants and scholarships increased by a factor of 7.7 from 1954-5 to 1962-3. As an example of Steacie's commitment to developing university research capabilities, rather than that of the NRC laboratories, we note the budget increase in 1958-59 of 70 % for university support compared to an increase of 7.8% for the NRC laboratories. In the last decade of NRC's control of grants and scholarships to universities, the budget was doubled from 45.5 M$ in 1967-68 to 92.8 M$ in 1976-77. Steacie's support of university research did not cause him to neglect the support of industry, as has been alleged by some, for it was Steacie who established the Industrial Research Assistance Program (IRAP), which is arguably the most successful industrial research support program partly because of its administrative simplicity.

Major Physics Facilities

A significant NRC contribution to physics in Canada has been the promotion of government support for major facilities that can be used by scientists throughout Canada (and other countries). Once approved, the NRC has assumed, in some cases, the responsibility for the provision, operation, or funding of these facilities. In other cases the NRC enters into agreements with other agencies, universities and governments, and is responsible for partial funding and jointly controls the overall operations of the facilities.

Astrophysics at NRC began in 1946 in the Radio and Electrical Engineering Division (REED) when A.E. Covington converted war-time radar equipment to undertake microwave observations of the sun. In 1970 the astronomical activities of the Department of Energy, Mines and Resources (EMR) were transferred to NRC and the Astrophysics Branch, under the direction of J.L. Locke, was created within REED. The Branch was responsible for three major astronomical facilities; a) the Dominion Astrophysical Observatory near Victoria B.C., which had been founded in 1918 with a 1.85 m telescope; b) the Algonquin Radio Observatory in Algonquin Park, Ontario with a 46 m reflector capable of operating at wavelengths as short as 8 mm; and c) the Dominion Radio Astrophysical Observatory near Penticton B.C., with two large arrays at 10 and 20 MHz and a 25.6 m paraboloid. The Branch also included the Upper Atmosphere Research Section started in 1955 under Peter Millman, which was concerned with aurora and meteoritics.

In 1957 D.C. Rose took on the chairmanship of the Canadian Organizing Committee for the International Geophysical Year (IGY) at a time when there was considerable confusion as to how Canada should participate. Rose brought together scientists from government, universities, and industry to carry out a research program which focused on the Canadian north, including certain features of the Auroral Zone and the North Magnetic Pole. This program made a major contribution to the IGY, the only countries to make greater contributions were the United States and the USSR. Rose also initiated space research at the NRC and built up an active group in the Physics Division. From this base he organized a number of projects involving government and university laboratories and Canadian industry. Eventually, the NRC took over (from the U.S. Army) the operation of the Churchill Rocket Range and a broad program developed using rockets and balloons to investigate the upper atmosphere and the near-earth space environment. This program not only created new opportunities for scientists, both in university and government laboratories, but it also had industrial benefits in terms of support for the development of the successful family of Black Brant rockets by Bristol Aerospace of Winnipeg, and the spawning of several companies.

During the 1960's and 70's there was a growing interest in space research in many countries. In Canada, the rocket program, and particularly the Alouette-ISIS satellite program, had stimulated considerable interest. In response to this interest the NRC in 1965 established the Space Research Facilities Branch to operate the Churchill rocket range. In addition to the launch operation, the Branch provided engineering support to scientists, mostly from universities, who participated in the program.

NRC's Physics Offspring

Over the years the NRC has given birth (not always easily) to a number of new organizations which have continued, and expanded, programs started by NRC. In 1946 it was decided to separate military and civilian research by establishing the Defence Research Board to take over most of the defence research that was being done at the NRC. Much of this work was physics related and had been started at the NRC during the war.

In 1952, Atomic Energy of Canada Ltd. was formed to take over the operation of the NRC nuclear energy program. The president of NRC, C.J. Mackenzie, was appointed the first President of AECL and he was replaced at NRC by E.W.R. Steacie.

In 1974 the government decided that the responsibility for providing a program of Grants and Scholarships to universities should be separated from NRC; the program was continued by NRC until the new agency, the Natural Sciences and Engineering Research Council (NSERC), was established in 1978.

Physics in NRC's Laboratories

We now consider a few highlights of physics research in the NRC laboratories, during the period 1945-75, chosen to demonstrate the wide range of research in physics at NRC.

Acoustics

The areas of study included ultrasonic absorption and hypersonic light scattering in liquids, radiation pressure, elastic waves in solids, sound-generating mechanisms in machinery, hearing protector design, the acoustics of circumaural earphones, and the design of acoustical instruments. Work on the absolute measurements of sound pressure formed the basis for Canada's primary acoustical standard. Research on the physics of the outer ear and sound propagation in the atmosphere was started. NRC's first anechoic chamber was designed and constructed in the mid 1950's.

Basic Standards

The Division of Physics expanded its work on developing the basic standards of measurements until, by 1959, it had established these standards in all the usual areas with a quality comparable to those at other major national standards laboratories. In 1970 the Time Service of Canada was transferred from EMR to NRC's Division of Physics. By 1958 the world's first continuously operating cesium clock was in operation as the primary time standard for Canada. NRC was one of the five major laboratories measuring perturbations and absolute wavelength values of the spectroscopic radiations that led to the redefinition of the International Metre in 1960, in terms of a transition in Kr^{86}. NRC was the only laboratory equipped to make all the three isotopic sources (Kr^{86}, Hg^{198} and Cd^{114}) being considered, and provided such lamps to the other four laboratories. NRC designed and built the first interference comparator for the routine measurement of standard metre bars in terms of wavelengths; the only time the US national metre standard was allowed out of the country was to be measured in this instrument. The iodine stabilized laser, still widely used as the de facto primary standard of length and wavelengths, originated at NRC in 1969.

Lasers and Plasmas

In June 1962 S.A. Ramsden joined the Physics Division and set up what was later called the Laser and Plasma Physics Section to work on high intensity lasers and the application of lasers to the production and investigation of dense plasmas. Following the development of the transverse-discharge, atmospheric pressure (TEA) carbon dioxide laser at DREV in 1970, a large CO_2 laser system was assembled and laser plasma interaction experiments were carried out with 10.6 µm radiation at intensities in the 10^{14} - 10^{15} W/cm^2 range.

Particle Physics

The world's first Microtron, a type of electron accelerator, was built at NRC in 1947-48 based on the proposal made independently by V.J. Veksler and E.M. McMillan in 1945. The Microtron could produce 8 orbits with a final electron energy of about 5 MeV and a current of 1 µA; it was eventually transferred to the University of Western Ontario.

From the 1950's, NRC played a substantial role in helping to build up particle physics in Canada. A number of particle physics projects were launched, including major initiatives such as TRIUMF, the OPAL experiment at CERN, and the Sudbury Neutrino Observatory. The key figure in triggering these developments in the 1960's and 1970's was Ted Hincks. He set up and guided the high energy physics program at Carleton University, was an early supporter of TRIUMF, brokered and identified NRC funding for Canadian participation at FermiLab, and had an important role in founding the Institute for Particle Physics, the collegial body that oversees the field in Canada.

In the 1960's and 1970's the work of the NRC High-Energy Physics (HEP) group was in the field of muonic atoms. They were the first group to use solid state counters to study this and, as a result, had a number of firsts: observation of muonic atom hyperfine structure in heavy elements, observation of nuclear polarization by muonic atoms, and a precision measurement of the vacuum polarization potential.

Radio Astronomy

Long baseline interferometry was first demonstrated in 1967 when a radio interferometer was set up amongst the radio telescopes at Algonquin Park, Penticton, Prince Albert, and Jodrell Bank in England.

Solid State Physics

In 1952 D.K.C. MacDonald arrived in the Physics Division and set up the Low Temperature and Solid State Physics Section, which was to attract a number of outstanding scientists and was to have a profound influence on solid state physics in Canadian universities and eventually in Canadian industry.

The results of low-temperature studies of thermoelectric power and anomalous resistivities in metals and alloys, begun by MacDonald and his colleagues (prior to his untimely death in 1963), led to an interest in Fermi Surface (FS) studies by the de Haas-van Alphen (dHvA) effect in the early 1960's. Newly available superconducting solenoids, and the development at NRC of very high precision absolute and differential measuring techniques (an improvement of more than 3 orders of magnitude) allowed, over the next two decades, for sufficiently precise measurement of FS dimensions that the effects of alloying and of hydrostatic pressure could be studied in detail. Valuable insight was gained into the effect of transition metal (magnetic) impurities in the noble metals, and it even became possible to test some of the fundamental predictions of dHvA theory.

Similar advances were made in studies of deformation processes in metals, in particular on fatigue failure and the relationships between dislocations and work-hardening. Other areas of study included specific heats, thermal and electrical conductivity, superconductivity, optical properties of solids, magnetic susceptibility, and Hall effect.

Spectroscopy

The spectroscopy section of the Physics Division was initiated with the arrival of G. Herzberg in 1948. The first four permanent staff members to join the section were Alex Douglas, Donald Ramsay, Hin Lew, and Cec Costain. They were respectively responsible for the construction of spectrographs and spectrometers for the visible, ultraviolet and infrared; a flash photolysis apparatus for studying the spectra of free radicals; an atomic beam laboratory; and a microwave spectroscopy laboratory. By the early 1950's the laboratory was equipped for studying problems in atomic and molecular spectroscopy from the microwave to the ultraviolet.

The section always had a large component of Post Doctoral Fellows and visiting scientists from many different countries around the world. The laboratory soon achieved the reputation of being the Mecca for spectroscopists and was visited by the most senior workers in the field. Among the early successes of the group was the realization that molecules frequently change shape on excitation to higher electronic states, e.g. linear to bent, and the discovery of the spectra of some simple free radicals such as NH_2 and HCO.

In 1971 Gerhard Herzberg was awarded the Nobel Prize in Chemistry "for his contributions to the knowledge of electronic structure and geometry of molecules, particularly free radicals." [19] The citation also noted that "Dr. Gerhard Herzberg is generally considered to be the world's foremost molecular spectroscopist and his large institute in Ottawa is the undisputed center for such research. It is quite exceptional, in the field of science, that a single individual, however distinguished, in this way can be the leader of a whole area of research of general importance. A noted English chemist has also said that the only institutions that have previously played such a role were the Cavendish Laboratory in Cambridge and Bohr's institute in Copenhagen."

Several universities in Canada and other countries have spectroscopy groups staffed by persons who served their apprenticeship in Ottawa. Of the members of the group, five have been awarded Nobel prizes and eight have been made Fellows of the Royal Society of London.

Surface Physics

Modern surface physics started in the 1950's with the development of ultrahigh vacuum techniques which allowed the preparation and maintenance of atomically clean surfaces for times long enough to conduct meaningful experiments. Much of this work on ultrahigh vacuum was pioneered at NRC. Surface physics studies were started in the late 1950's, including work on thermal desorption spectroscopy, electron stimulated desorption, physical adsorption, and ionic entrapment in solids.

THE LAST QUARTER CENTURY: 1975-1999

The shift of NRC's financial support from its laboratories to university and industrial research accelerated in the 1960's ; in 1958 the NRC laboratory operations took 65% of the budget, and extramural support (industry and universities) took 20%; by 1967 the corresponding figures were 35% and 55%. By the 1970's scientific research in Canadian universities had reached world standards with the help of NRC's, programs of Grants and Scholarships so that NRCs initial objective had been reached. When NSERC assumed the major role of supporting university research in 1978, NRC's prime role became the support of R/D to advance Canada's industry. As a result, the proportion of basic research in NRC laboratories decreased from 25% in 1977-8 to 15% in 1980-1.

During the last quarter of the century NRC has made many improvements in support programs for industrial R/D and arranged reorganizations of the NRC laboratories intended to facilitate the transfer of technology to industry. In 1975 the PILP program (Program for Industry-Laboratory Projects) was started to fund the exploitation by industry of marketable products conceived and developed in NRC laboratories.

In 1987 the Canadian Space Agency was set up to bring together a number of programs that existed in NRC and other government departments. Three programs initiated by the NRC now form an important part of the activities of the Space Agency; these are the Space Science Program, the Astronaut Program, and the Space Station Program. L. Kerwin, then President of NRC, became the first President of the new Space Agency.

Major Physics Facilities

In the period 1975-99 the NRC maintained its responsibilities to promote and support major physics facilities for use mainly by university researchers, in several cases with other agencies or governments providing partial funding.

When the original proposal for the construction of a synchrotron light source in Canada was turned down, the NRC provided the finances for the construction of a Canadian beam-line on the synchrotron light source at the University of Wisconsin (1979) to be operated by the University of Western Ontario; in 1988 a second beam-line was added. A second proposal for a Canadian synchrotron light source at the University of Saskatchewan was approved for funding by the federal and provincial governments and other agencies in March 1999.

The TRIUMF accelerator at the University of British Columbia was originally funded by the federal government through the Atomic Energy Control Board. In 1976 the responsibility for the supervision of the federal government's interests in TRIUMF was transferred to NRC. By 1977 the proton beam at TRIUMF was greater that 100 μA at 500 MeV. The controversial proposal for the Kaon Factory addition to TRIUMF was discussed for several years and finally failed to get federal government financing in 1994.

In 1976 the NRC obtained new funding for support of a space science program and the Canada Centre for Space Science was established under the directorship of Ian B. McDiarmid. The Centre's mandate was to develop a broadly based program involving university and government scientists and Canadian industry. Since Canada had no launch capability, collaborative research programs were negotiated with space agencies of other countries. Space instruments were developed in scientist's laboratories and final test flight units were built and tested in industry. Instruments were flown on many foreign satellites and Canadian scientists became internationally recognized, particularly in the fields of imaging from space and analysis of charge particle populations in space.

NRC represented Canada in negotiations with France and the government of Hawaii to construct the Canada-France-Hawaii Telescope at the top of Mauna Kea on the island of Hawaii. The 3.6 m diameter mirror was ground and polished at the optical workshop of the Dominion Astrophysical Observatory near Victoria. The telescope was in operation by 1979. In 1987 an agreement was reached by NRC for Canada to take a 25% share in the construction on Mauna Kea of the James Clerk Maxwell radio telescope, jointly with the British and Netherlands governments. This 15 m radio telescope, is capable of observations in the 4 to 0.3 mm wavelength range. NRC is representing Canada with a 15% stake in the Gemini Project, in collaboration with NSERC and WESTAR, which is constructing twin 8 m telescopes, usable in the optical and infrared, on Mauna Kea, Hawaii and on Cerro Pachon, Chile. The NRC laboratories are undertaking a substantial part of the Gemini Project, in instrumentation and software development. First light on the telescope on Mauna Kea was achieved in 1998.

NRC and the University of Calgary are planning a Square Kilometre Array (SKA) radio telescope. About 30-40 parabolas would reflect the incoming radio waves from space onto a 5 m receiving antenna suspended from a balloon. It is hoped to build a \$5 million prototype early in the new century.

In 1978 NRC was assigned responsibility for co-ordinating fusion energy research; this led to the funding of the Tokomak de Varennes, jointly with Hydro-Québec, in 1981.

The initial planning for the National Optics Institute was undertaken by the staff of the Physics Division, and the Institute was established in Ste. Foy in 1986.

NRC exercised a strong catalysing role in starting the Sudbury Neutrino Observatory, particularly in bringing together the large collaboration required, preparing the original proposal, and ensuring support by the federal government. NRC laboratories were involved in measuring the attenuation of light in heavy water, in measuring the optical properties of acrylic, developing inductively-coupled plasma mass-spectrometry techniques to measure femtogram amounts of thorium and uranium in heavy water, and development of a TPC detector for low-level radon counting. NRC has made budget outlays totaling about $20 million to the SNO project, starting with funds for the exploratory drift in the Creighton mine in 1986. Neutrinos were first observed in May 1999.

In 1999 the NRC and AECL made a joint proposal to government for the construction of a Canadian Neutron Facility intended to provide an advanced materials research capability for use by Canadian universities and industry and to be used as a test facility for improved reactor design. If funded, the facility is expected to come on line in 2005.

Physics in NRC's Laboratories

In spite of severe budget cuts, reductions in staff, and several reorganizations, the quality of physics research at the NRC laboratories has remained high. Between 1984 and 1991 the NRC budget decreased by 100 M$ (in 1984 dollars) and the total staff decreased by 18%. A drastic reorganization of NRC occurred in 1990 which was intended to improve the laboratories' ability to assist Canadian industry and to concentrate basic research activities; more than 200 employees took voluntary layoff.

A major reorganization of the divisional structure of the laboratories occurred in 1990 when it was decided that the traditional title of 'Division' for a major laboratory grouping at NRC was no longer appropriate and the title 'Institute' substituted. Disciplinary titles such as Physics or Chemistry were also eliminated as being too academic. The Division of Physics was subdivided into the Institute of Microstructural Sciences (solid state physics and technology) and the Institute of National Measurement Standards (basic measurement standards), the basic physics activities were transferred to the Herzberg Institute of Astrophysics and the new Steacie Institute of Molecular Sciences. About 300 staff members (person years) were eliminated from NRC and the funds thus released were applied to the operating and capital budget. In 1995 it was announced that the NRC budget would be further reduced by 76.2 M$ over 3 years.

In 1995 the activities of the Herzberg Institute of Astrophysics based in Ottawa, other than spectroscopy, were moved to the site of the Dominion Astrophysical Observatory near Victoria. A few highlights of physics research in the NRC laboratories in the period 1975 to 1999 are noted below.

Acoustics

Today, as a result of close collaboration with the Acoustics Section, the high-fidelity loudspeaker industry has grown and Canadian-made loudspeakers are recognized as being amongst the best in the world, with Canadian manufacturers occupying an important share of the North American market. In 1989, NRC established the Canadian Audio Research Consortium (CARC), with members from the industry, to explore the audio technology required to continue building competitive loudspeakers well into the next decade.

Astrophysics

Research in optical astronomy, radio astronomy, space physics, upper atmosphere research, and laboratory astrophysics was transferred in 1974 to the newly created Herzberg Institute of Astrophysics (HIA), named in honour of Gerhard Herzberg. The HIA was also made responsible for the Algonquin Radio Observatory (NRC support for ARO ended in 1987), the Dominion Radio Astrophysical Observatory in Penticton, and the Dominion Astrophysical Observatory in Victoria. Observing time with the DAO and DRAO telescopes, the James Clerk Maxwell Telescope and, soon, the Gemini telescopes are available to all astronomers; time is allocated by Time Allocation Committees. In some cases it is not necessary for the visiting astronomer to be present; observations can be taken by staff astronomers. In 1986 the Canadian Astronomy Data Centre was established at DAO to create special software for astronomical data archives.

The principal instrument of the DRAO is now the Synthesis Radio Telescope which consists of seven 9 m paraboloids on an east-west axis, 600 m long. It is currently used to survey the Galactic Plane at frequencies of 408 and 1420 MHz.

Optics

A research program on optical interference coatings resulted in the development of advanced techniques for the computation and production of optical filters and reflectors that have been of great value to Canadian companies and universities. A familiar example is the iridescent anti-counterfeiting device used on Canadian currency which was developed in the Physics Division; a modified form of this system is used for special inks on the currencies of fifty countries.

In the process of redefining the International Metre, by reference to a Cs clock and a conventional value for the velocity of light (c), a unique frequency comparison chain was built at NRC, in 1979, to lock optical radiation (Kr^{86}) to a microwave frequency standard. In 1983, this was used to provide one of three independent determinations of c, in terms of the old standard, that was required to define the present International Metre. In the same year inter-comparisons of time standards were made via satellite links amongst the NRC, the National Bureau of Standards in Boulder, Colorado, the US Naval Observatory in Washington, and the Bureau des Poids et Mesures in Paris. The first direct measurement of the frequency of visible radiation was made at NRC. Recently the frequency of visible radiation (at 674 nm), locked to a transition in a single trapped cesium ion, was measured to form the basis of a new time standard.

A program of research in photogrammetry, which arose naturally from the early work on aerial photography, placed Canada in the forefront of aerial mapping techniques and, in particular, produced the first digital analytic plotter, a development that revolutionized the process of map-making throughout the world.

An example of research in modern optical physics at NRC is that of the Femtosecond Research group which is concerned with electronic relaxation and energy flow in molecules using time resolved photoelectron and photoionization spectroscopy, and also with control of dynamic processes and material properties with optical phase. A highlight of this work is the development of a method of isotope separation using the quantum mechanical rephasing of nuclear wavepackets in diatomic molecules by femtosecond laser pulses.

During the 1980's, a collaboration between NRC and Lumonics Inc. resulted in the development of several large aperture, multi-atmosphere CO_2 laser amplifiers. This culminated in the development of a 1 terawatt laser system, which generated nanosecond duration infrared pulses with an energy of 1 kJ, and the focused output created intensities as high as 3.1015 W/cm^2. Another collaboration involved the Laser and Plasma Physics Section and the Lawrence Livermore National Laboratory (LLNL). A direct result was the construction of a 300 J Nd:glass laser system, based on components provided by LLNL from the decommissioned SHIVA laser. Using the glass laser it was possible to create plasma conditions that provided significant gain from transitions in Ne-like Ge, and experiments in collaboration with researchers from the Université du Québec and the University of Toronto resulted in the demonstration of Canada's first XUV laser at 23 nm.

Particle Physics.

The High Energy Physics section of the Physics Division was moved to Carleton University in 1978 so as to be in closer contact with the university group working in the same field. In 1990 the staff and equipment of the HEP section were transferred from NRC to Carleton University.

In collaboration with researchers from TRIUMF and the universities of Carleton, Montreal, and Victoria, the first operating Time Projection Chamber (TPC) was developed to search for a rare muon decay mode. The OPAL detector project at CERN, started in the early 1980's and installed on the LEP collider, is now in its final phase of operation; there are about 250 collaborators from several countries. The OPAL detector measures results of e + e- collisions from the mass of the Z_0 particle (91 GeV) to 200 GeV in the centre of mass. The Canadian component of this collaboration was started by NRC and expanded to include TRIUMF and the universities of Alberta, Carleton, Montreal and Victoria. About 50 Canadian physicists are involved in OPAL. It is estimated that the total Canadian contribution during the construction phase was $15 million, divided between NRC and NSERC. Over 40 papers per year have been published by the collaboration including;
1) measurements to show that the number of neutrino species is restricted to three, 2) precision measurements of the Z_0 mass and width, allowing the mass of the top quark and the Higgs boson to be inferred, and 3) the Weinberg angle.

Solid State Physics

By 1975 there were noticeable changes in solid-state physics research from studies in crystalline solids to the study of thin films and quantum (layer) structures, many of these in semiconductors rather than metals. By the 1980's the trend was towards the support of the semiconductor industry. Basic research became concerned with the fundamental electronic and optical properties of systems of reduced dimensionality, and with the study of new phenomena, such as the quantum Hall effect, and photoluminescence in quantum wells and superlattices.

The Institute for Microstructural Sciences (IMS) established the first Molecular-Beam-Epitaxy facilities in Canada and was early on the scene in the fields of mesoscopics and nanoelectronics, setting up a project in the late 1980's. The program includes research into lithographic and growth techniques for making nanodevices, and experimental and theoretical studies of their novel properties such as the 'Coulomb blockade' single electron charging effect, which will probably form the basis of future electronics. The program has included the first spectroscopic investigations of few-electron lateral quantum dots (artificial atoms). The program has resulted in many international collaborations, including formal programs with European nanoelectronic centers (ECAMI and CERION) and with Taiwan.

Research on the optical properties of semiconductors was built up; in 1989 NRC established the Solid State Optoelectronics Consortium (SSOC) bringing together members from industry, universities and government to explore the emerging subject of optoelectronics. The SSOC collaboration has developed several new technologies, including 1.5 mm QW lasers, circular grating lasers, distributed feedback lasers, and an optical time domain reflectometer. Research on the physics of optical processes in quantum wells has laid the groundwork for rapid advances in an area of enormous current interest to the telecommunications industry. Recently it has led to basic research concerned with the fabrication and understanding of quantum dots. The first quantum dot laser with emission in the red was demonstrated at IMS in 1996 using self-assembled growth to control the semiconductor epitaxy on the atomic scale in all three dimensions. Such high-quality nanostructures are now obtained in a wide-range of wavelengths with good uniformity and reproducibility, and are engineered to produce devices with enhanced and/or unique properties.

Spectroscopy

In the last 25 years the introduction of laser spectroscopy, the extensive use of double- and multi-resonance methods, and the replacement of grating spectrographs with Fourier-transform interferometers has caused a considerable change in experimental methods. With these new tools, extensive work has been done on molecular ions (Oka and Amano), van der Waals and other non-rigid molecules (McKellar), and more recently on metal-containing molecules (Simard). In 1980 Oka discovered the infrared absorption spectrum of H_3^+ in the laboratory; this has since been identified in emission from the hydrogen-rich planets such as Jupiter and Saturn and in absorption in interstellar space. The search for H_3^+ had a serendipitous spin-off in the discovery of the emission spectrum of neutral H_3 by Herzberg in 1979; this molecule had stable Rydberg states but no ground state.The study of this and similar emission spectra of neutralized closed-shell molecules was a laboratory theme for many years; this included the rare gas hydrides, which started with the spectrum of ArH discovered by Johns in 1970, and the analysis of the spectrum of NH_4 by Watson in 1984.

Surface Physics

By the 1970's surface physics and surface chemistry had become almost indistinguishable and were renamed surface science. In 1984 the various groups involved in surface science and solid state physics in the Divisions of Physics, Chemistry, and Electrical Engineering were combined in what later became known as the Institute for Microstructural Sciences; the basic research in surface science continued but emphasis was placed on interactions with Canadian industry. Facilities were built up for molecular beam epitaxy, together with x-ray, electron, and ion lithography and instruments for several surface spectroscopies.

SUMMARY

For the last 84 years the National Research Council has supported the physics community in Canada and, since 1925, has maintained research in physics and astrophysics in its own laboratories. When NRC was founded in 1916 there was little physics research in Canada. From 1916 to 1939 the priorities were, 1) expanding physics research in Canadian universities through programs of grants and scholarships, and 2) establishing the NRC laboratories to conduct R/D related to industrial and governmental needs, the latter being severely restricted by lack of government support. During the war NRC took a leading position in the development of radar, nuclear energy, and other physics-related wartime R/D. The credibility gained by NRC's wartime activities resulted in increased government support after the war. The support of university research in physics was greatly expanded while physics at the NRC laboratories expanded slowly and more basic research was undertaken. NRC became the national standards laboratory for Canada by developing and maintaining the basic standards of physical measurements. In 1970 NRC took over all astrophysical research in government.

In the 1960's NRC came under attack, as did national laboratories in many other countries. The result was the transfer of the university granting function from NRC to NSERC, in 1978, and the shift of NRC's first priority to the support of industrial-related research. NRC maintained its responsibility for the support of major facilities in physics and astrophysics for use by universities and industry. Budget and staff cuts in the 1980's and early 1990's led to reorganizations of NRC's laboratories and caused significant loss of morale. As the century ends, physics and astrophysics in the NRC laboratories have recovered from the worst effects of the cuts, and both basic research and R/D in support of industry are of high quality.

VALEDICTION

As the century drew to a close, Gerhard Herzberg, who had done so much to foster physics at NRC and in all of Canada, died on March 3rd, 1999 at the age of 94 [20].

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