THE GREAT LEAP FORWARD: NRC AND THE MICROSCOPIC STRUCTURES AND TRANSFORMATIONS OF MATTER

BY ALBERT STOLOW

While Physics deals with matter and energy, the world of physics research is human. Discovery and innovation emerge from individual creativity, collaboration, engineering advances and cultural receptivity—all of which influence the progress of science. As we revisit NRC's 100 years of contributions to physics, we celebrate our pioneers in chemical physics, epitomized by the 1971 Nobel laureate G. Herzberg.

As someone who has had the good fortune to be a part of NRC's chemical physics story, I am pleased to have the opportunity to share a few personal views on NRC's outstanding legacy.

THE GREAT LEAP FORWARD: THE STRUCTURE OF MATTER

Classical physics describes the everyday world of projectiles, bridges and balls rolling down hills. It fails dramatically in the microscopic world of electrons and atoms – and especially for their interactions with light. In a sense, quantum mechanics was forced upon us by the need for an explanation of the light absorbed or emitted by atoms, or, for the case of black body radiation, matter in general.

One hundred years ago, physicists had little idea of the structure of atoms, molecules or solids. It is hard for us to imagine that, in 1900, even their existence was hotly debated, with L. Boltzmann taking the side of the Atomists and E. Mach the side of the Energists. Boltzmann was greatly depressed and, tragically, took his own life in 1906, seemingly unaware that Einstein had presented some of the most compelling support for the atomic theory just the year before. Quantum theory, in combination with the light-matter interactions of spectroscopy and diffraction, led to a great leap forward for humankind: an understanding of the microscopic structure of matter. It is hard to overstate the significance of this development. Quantum mechanics and spectroscopy gave us the detailed structure of molecules, solids, biomolecules, drugs, etc. It led to the development of things we take for granted today, such as computers, semiconductors, transistors, the atomic bomb and pharmaceuticals. In the field of molecular biology, it helped us understand the shape of DNA molecules and make predictions that opened doors to vast new fields, including genetic engineering.

SUMMARY

As we revisit NRC's 100 years of contributions to physics, we celebrate our pioneers in chemical physics, such as the 1971 Nobel laureate, Gerhard Herzberg.

MOLECULAR SPECTROSCOPY—THE STUDY OF STRUCTURE

Spectroscopy, the study of the interactions between electromagnetic radiation and matter, was critical to the development of our fundamental theories, including quantum mechanics, relativity and quantum electrodynamics. To date, more Nobel prizes (currently 76) are related to light-matter interactions than any other discipline in physics.

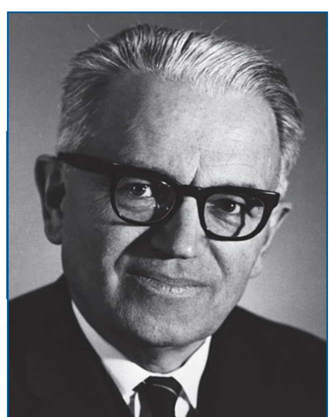

Fig. 1 Gerhard Herzberg, the Father of Molecular Spectroscopy, spent over 50 years at the NRC. Source: NRC Archives

In this domain, NRC played a pivotal—and Nobel Prize-winning—role thanks to Gerhard Herzberg (Fig. 1), the father of molecular spectroscopy, who was a member of NRC's Division of Physics for nearly 50 years. Herzberg's spectroscopy taught the world about the detailed structure of molecules, arguably one of the most significant contributions to our understanding of nature.

At the 1971 Nobel awards ceremony in Sweden, S. Claesson of Royal Academy of Sciences summed

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up Herzberg's immense stature in the field: "... 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." [1]

At Herzberg's birth in 1904, the concept of an electron was just catching on. When he attained his PhD in 1927, researchers had yet to discover how atoms combined to form molecules. Herzberg continued his studies at the University of Göttingen, Germany – the birthplace of quantum mechanics – working with Max Born and James Franck. After immigrating to Saskatoon in 1935, Herzberg joined NRC's Division of Physics in 1948, and remained active until 1994. In 1975, NRC established the Herzberg Institute of Astrophysics.

NRC became the world centre for molecular spectroscopy, receiving visitors and post-doctoral scientists from around the world. These included luminaries such as A. Dalgarno from Harvard, H.C. Longuet-Higgins from Cambridge and the future Nobel prizewinners D. Herschbach, R. Curl and H. Kroto.

Herzberg's legacy also includes his trilogy of books on molecular spectroscopy, nicknamed the "Spectroscopy Bible". According to Herzberg biographer and former NRC researcher Boris P. Stoicheff, he "... devoted Saturdays for fifteen years to the writing of this book, no matter whether he was in Ottawa or on travels to conferences or on other business. At the NRC we all understood we would not see him on Saturdays." [2]

Fig. 2 EWR (Ned) Steacie was a leading chemical kineticist who additionally became an NRC President and played a seminal role in developing science policy within Canada. Source: NRC Archives

Today, spectroscopy is in use everywhere, whether in quantum devices, chemical sensors, medical devices or an endless array of analytical equipment. In a very real sense, NRC's investment in molecular spectroscopy changed the world.

CHEMICAL KINETICS AND DYNAMICS: THE STUDY OF CHANGE

Nature is seldom static. There is therefore a need to understand how molecular systems change and evolve: this is the field of chemical kinetics. A world leader in chemical kinetics was Montreal native E.W.R. (Ned) Steacie (Fig. 2), a successful professor and internationally-acclaimed research authority in free radical kinetics. Under Steacie, NRC became a centre for kinetics and chemical dynamics, attracting students and researchers from around the world, including future Nobel prize winners J. Polanyi and R. Marcus. Importantly, Steacie wrote the kineticist's "bible"–*Atomic and Free Radical Reactions* (1946)–that became the essential reference book for the field. At NRC, Steacie became Director of the Division of Chemistry and then NRC President, where his influence on science policy greatly increased Canada's scientific infrastructure and capabilities. He also created the NRC postdoctoral fellowship program that contributed greatly to the vitality of NRC laboratories.

Although Herzberg and Steacie stand out, NRC's legacy in chemical physics comprises other pioneering giants. These include F. Lossing for Mass Spectrometry, H.J. Bernstein for the Resonance Raman Effect, W.G. Schneider for High Resolution NMR and W. Siebrand for Theoretical Chemical Physics.

In a real sense, my own scientific career derives from the legacies of both Herzberg and Steacie. The Ultrafast Phenomena Group of NRC's Steacie Institute for Molecular Sciences (SIMS), founded in 1990 by P.B. Corkum, comprised elements from both legacies. Following my PhD studies in chemical dynamics under J. Polanyi (Toronto), I joined colleagues D.M. Villeneuve, M. Yu. Ivanov and Corkum in 1992 to work on another offshoot of spectroscopy, the ultrafast laser, and to develop new forms of ultrashort pulse (femtosecond, 10^{-15} s) laser spectroscopy.

We developed powerful new methods of ultrafast spectroscopy for making real-time "movies" of chemical reactions, trying to understand how atoms and electrons dynamically rearrange during a chemical reaction. This eventually led to my founding of NRC's Molecular Photonics Group, still very active today, and my ongoing interactions and collaborations with NRC. Ultrafast molecular spectroscopy has improved our understanding of fundamental processes, such as photosynthesis and vision, and has led to advances in molecular devices, photoactivated drugs, catalysts and other light-responsive materials. P.B. Corkum went on to pioneer a completely new branch of physics, namely attosecond (10^{-18} s) science, which uses the world's shortest laser pulses to probe electronic processes in atoms, molecules and solids.

BUILDING ON THE LEGACY

An interesting offshoot of ultrafast laser technology is the development of nonlinear optical microscopy, a field initiated by W. Webb at Cornell University. Normally at low power, light interacts with matter linearly, with the linear optical response containing the refractive index and the absorption coefficient. However, when an intense ultrashort pulse is applied to matter, a nonlinear optical response develops, leading to the possibility of many new forms of spectroscopy.

A recent example is a new kind of microscopy of live cells, materials and minerals. Combining femtosecond lasers, nonlinear optics and quantum control with spectroscopy, we optimized a rapid label-free, chemical-specific imaging method based on a third order nonlinear response termed Coherent Anti-Stokes Raman Scattering (CARS). Importantly, the method allows for real-time imaging of live cells without adding any dyes or stains, as shown in Fig. 3. In 2009, NRC's femtosecond laser approach led to the first commercially available CARS microscope, developed in collaboration with Olympus Corp. The method has also been applied to imaging the distributions of specific compounds, such as hydrocarbons or valuable minerals, within ores and rocks, thus opening up a new field: "geophotonics".

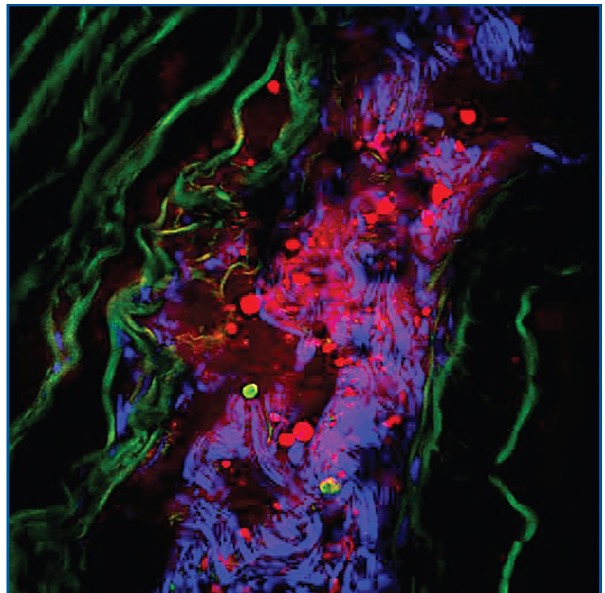

Fig. 3 A femtosecond (10^{-15} s) laser method of Coherent Anti-Stokes Raman Scattering (CARS) was developed by NRC in 2007, allowing for rapid, label-free yet chemical-specific imaging of live cells, tissues, materials and minerals. The multi-modal CARS image shown above is an unstained sample of aorta from an atherosclerotic rabbit: the red shows telltale lipid droplets, the blue collagen and the green elastin. In 2009, NRC commercialized the world's first CARS microscope in collaboration with Olympus Corp. Source: Image courtesy of Albert Stolow

Underlying the NRC's 100 years of outstanding Physics research, there have always been individuals whose personal drive and curiosity led to puzzles and discoveries, dead ends and new fields, theories and innovations. This is certainly true for chemical physics and NRC's outstanding legacy in this field continues to serve Canada well. There may well be more Nobel prizes on Canada's scientific horizon, but such outcomes only reflect a sustained and serious creative effort. I would like to conclude with a quotation from a speech given by Gerhard Herzberg at a 1971 Rideau Hall banquet, celebrating the recent announcement of his Nobel Prize:

> *"… the Nobel foundation considers the Prizes in the Sciences to have the same purpose as the Prize in Literature, namely to reward contributions to the human spirit, i.e., to the cultural benefit of mankind. In science, of course, such contributions often lead to material benefits to mankind. Since one cannot predict discovery, these material benefits are usually quite unexpected and not foreseen by the scientists involved (nor of course by anyone else). The motivation of many scientists working in pure science is striving for knowledge for its own sake."*

REFERENCES

1. http://www.nobelprize.org/nobel_prizes/chemistry/laureates/1971/press.html
2. *Gerhard Herzberg: An Illustrious Life in Science*, Boris P. Stoicheff, National Research Council Canada.