INSTITUTE for
QUANTUM STRUCTURES AND QUANTUM DEVICES
(CFI International application)

Vision

We envision a multi-national centre, based in Vancouver, for basic research towards enabling technologies, which incorporate quantum properties in an essential way leading to new kinds of ‘quantum devices’. The main thrust is to parallel the very successful but fundamentally limited approaches of tweaking properties of known systems for optimal performance with a strong effort in radically new approaches based on theory and new methods of materials and device fabrication. The new institute will build upon existing strengths in Vancouver. It will involve groups of researchers and several institutes in the USA (mostly from Stanford) and corporate research labs such as IBM, Australia (notably the Univ of New South Wales), and Japan (Univ of Tokyo) in an essential way- this will involve sharing of personnel and infrastructure, along with exchange and joint research agreements. It is intended that the infrastructure in Canada will complement that in these foreign centres. The institute will also involve Canadian partners, again with complementary infrastructure- these include NINT , SFU, the Univ of Alberta, and the Univ of Sherbrooke..

The local Vancouver effort will build upon 2 existing strengths, viz.,

(i) A large UBC group of experimental condensed matter physicists, chemists, and engineers, which is still growing to a planned total core complement of over 20 professors, and whose focus is on quantum materials, quantum devices, nana technologies and fundamental studies in new kinds of solid-state quantum systems. Many of these researchers have laboratories in the Advanced Materials and Process Engineering Laboratories (AMPEL).

(ii) The new Pacific Institute for Theoretical Physics (PITP), which is an international institute covering most fields of theoretical physics. The main input from PITP will come from the existing ‘Quantum Condensed Matter” network, which includes 3 Nobel laureates in physics, and the “Complex Systems” network.

In the last few years UBC has been building up a large and strong cluster of scientists in research areas in which quantum structures, quantum materials, and applications towards quantum devices are central. At the same time a very strong theoretical research group in this area has been assembled. This has involved the hiring so far of 15 experimental physicists and chemists, 8 engineers, plus several experimental biophysicists, and 7 theorists working in quantum condensed matter physics (along with 1 biophysics theorist). This hiring plan is by no means complete- it is intended that another 10 experimentalists working in this area be hired in physics and chemistry, as part of a university plan. At the same time we have built up a large collaborative research effort between UBC and Stanford (involving now 12 different research collaborations between the 2 institutions, as well as a number of cross appointments) and involving the national nanofabrication center at Stanford, and more recently, between UBC and the Australian ‘centre of excellence’ based in Sydney (with an important branch in Brisbane). In addition there are strong collaborations recently started with spintronics center at IBM Almadin and the Stanford Synchrotron radiation center.

The key idea behind this very large effort is the development of new technologies and devices based on essentially quantum ideas like interference, coherence, and even entanglement, along with the design of new quantum materials and quantum structures starting from microscopic theory (both analytic and computational). It is by now fairly well understood that we are on the threshold of a new technological revolution involving the design and fabrication of new exotic materials and of quantum devices based on magnetic, quantum dot, and superconducting components, built from nanofabricated metallic, semiconducting, and insulating structures, or even directly from molecules or atoms.

Much of the progress achieved so far would have been impossible without
(a) fundamental new theoretical insights in solid-state physics, and Chemistry.
(b) the development of new enabling technologies such as nanoscale fabrication and assembly techniques, and new nanoprobes like the STM, optical tweezers, sub atomic resolution electron microscopy, X-ray microscopy and holography using synchrotron radiation techniques

The theoretical insights include the understanding of exotic new strongly-correlated systems like the Quantum Hall fluids, supersolids, superfluids and superconductors, quantum magnets, low-dimensional quantum systems, complex materials based on transition metal compounds or organic groups, and large-scale quantum phenomena (including the understanding of decoherence and dissipation mechanisms in magnetic, superconducting, and semiconducting systems). They also include a quite revolutionary new ability to realistically model complex quantum systems numerically, using new methods like dynamic mean field theory, density functional methods like LDA and LDA+U, diagrammatic quantum Monte Carlo methods, or the 'Carr-Parinello'molecular dynamics techniques. As a consequence of this we envisage a new kind of '***designer***' quantum technology, in which new materials with properties depending essentially on the multi-particle quantum wave-functions can be designed and built to spec, and incorporated into entirely new kinds of quantum structures. The properties of materials and devices are determined by the basic electronic structure and the elementary excitations that in turn determine the response to external stimuli. In the new generation of materials and devices it will be not only the charge degrees of freedom and charge transport that play a central role but also other degrees of freedom with much less dissipation such as the spin as well as orbital degrees of freedom. In the new generation of materials we will not only rely on known properties of known compounds and molecules and using these as building blocks in devices of composite materials but rather use theoretical predictions with regard to properties of the interfaces themselves of very dissimilar materials and the quantum confinement present in small-scale structures. These new classes of systems and materials whose properties are determined by interfaces and structures of interfaces open up a whole new world of possible properties. Based on these interface engineering concepts new materials and devices are being dreamt of and in fact are just beginning to appear displaying giant: electric capacity, magneto caloric, magneto electric, magneto capacitive, magneto resistive and, thermoelectric properties which will most certainly play a determining role in the improvement of the quality of life. In much of this development the spin of the electron is beginning to play a role as important as its charge. The manipulation of the spin or magnetic moments can be done at a distance without direct contact and without the strong dissipation encountered by the movement of charge. This control and monitoring at a distance will play central roles in modern devices but also in quite obvious applications in the bio-medical area. For example a carbon nanotube filled with a magnetic material can be manipulated inside the human body with external magnetic fields brought to a location of interest and then excited with a radio frequency magnetic field to destroy unwanted cells at that location. Actually the first step of producing such filled nanotubes has recently been made.

The new advances in experimental physics, chemistry and engineering crucially involve new fabrication tools and probes. These include scanning tunneling probes with sub atomic resolution, spectroscopic and electromagnetic tools in the X-ray, optical, and microwave range, electronic spectroscopy to directly probe the quantum states of electrons in solids and interfaces, micro SQUIDs, and electron and x ray holographic tools, photonic manipulation (e.g., optical tweezers), spin manipulation, and nascent attempts to manipulate quantum phases in superconducting, magnetic systems and quantum dot systems. The transformation of optical techniques to the X ray wavelengths is of great importance because of the spatial resolution limitations accompanying optical microscopies. X ray microscopes with spatial resolutions in the nanometer range are on the horizon and will become reality with the development of the 4th generation synchrotron sources based on the principles of free electron lasers. To do any of this requires sophisticated preparation facilities, including single crystal synthesis, and synthesis and self-assembly at scales from macromolecules and nanoparticles down to atoms and atomic clusters. It also requires nanostructuring (e.g., multi-beam Molecular Beam Epitaxy, to prepare novel 'designer' multilayer structures with atomic resolution at low T; electron beam lithography with nanometer resolution, Focused ion beam etching, etc.), and the fabrication of non-standard materials and devices (far from Si), such as functionalized magnetic, molecular, superconducting, and photonic arrays, switches, etc. Other nanostructuring and nanofabrication facilities of central importance include fully equipped cleanroom facilities, and modern surface analysis facilities such as scanning Auger, XPS, and time of flight secondary ion mass spectrometry as well as high resolution electron microscopies.

With this battery of new techniques, experimental and applied physics and chemistry are beginning to expand rapidly away from traditional studies of semiconductors, metals, and simple magnets and superconductors, to embrace exotic new quantum systems ranging from artificially engineered systems like the 'Quantum Corral' or arrays of molecules, spins, quantum dots, superconducting devices, etc., to hybrid materials involving organic and inorganic components- the new variety of physical systems is quite bewildering.

There is now a world-wide race going on to achieve what is sometimes called "***convergence***", in the emerging new technologies based on these theoretical and experimental developments. These technologies involve many different elements, from information technology (including new kinds of information storage and processing device), communications, nanoengineered platforms for gene and drug delivery, new kinds of microprobe for sensing everything from magnetic and electric fields to pressure and chemical environment, and an enormous array of new materials, both single and composite, at length scales ranging from sub-nanometre up. The idea of "convergence" is that as these new technologies are brought together, a 2nd industrial revolution will result, with huge (and largely unpredictable) long-term consequences. It is widely hoped that out of this revolution some long-term solutions to really pressing problems may emerge. Examples commonly cited are (1) new kinds of energy technology (as a solution to the problem of renewable energy resources); (2) new kinds of information processing system (including quantum information processing); and (3) a wide array of quantum devices based on superconducting junctions, magnetic quantum wires and molecules (including spin chain molecular systems), quantum dots, and paramagnetic and nuclear spins.

The point we wish to emphasize here is that a central part of this revolution involves quantum mechanics, and that there is a pressing need for a centre that directly addresses this, instead of trying to solve problems in isolation. Our vision is that in the not to distant future we will be operating in a world in which quantum mechanical effects will play the dominant role in defining the functionality of new devices and materials. We are at the beginning of an intellectual revolution which will, if we can meet the challenge, revolutionize computation, information storage and transmission, devices based on the transport of charge and spin, energy storage and production, biomedical devices and in vitro body function monitors. This intellectual challenge demands the use of quantum interference and coherence effects, quantum entanglement, fractionalization of quantities like spin and charge, and quantum mechanical transport of charge and spin without dissipation. Starting with ideas and predictions from theoretical physics, experiments will be set up to study the properties of engineered materials and devices based on quantum phenomena, and with fundamental features that can only be achieved by drawing upon quantum mechanics.

From this point of view the examples (1)-(3) mentioned in the penultimate paragraph should be viewed as spin-offs or crucial by-products of the work of the planned centre- indeed they cannot be achieved without first grappling with more basic problems (to be discussed more below). It makes no sense, for example, to try to develop new kinds of information technology (which will ultimately be quantum mechanical) without first dealing with the fundamental problem of decoherence and the mechanisms controlling it- and this is a problem requiring important new theoretical and experimental work. In the same way a solution to the problem of renewable energy resources will not come by just attacking it head on- fundamental new ideas are required, many of which will have to come from a combined theoretical and experimental study of quantum materials.

B. Research Goals

Our general goal is to create a centre that will seed the development of new kinds of quantum device, new quantum materials, and in general provide the basis for new quantum technology.
Without attempting a systematic discussion, some of the more specific ideas and planned research goals, for both structures and devices, include:

1.Magnetic cluster molecules on 2-dimensional electron gas structures, with interactions controlled by gate voltages in FET-like structures. Can we control the decoherence and the interactions sufficiently to make a multi QUBIT device for quantum computing? The production of artificial (magnetic) molecules using quantum dots with magnetic atoms or molecules, coupled by engineered combinations of electrodes to function as gates to control the coupling. The development of spin-based arrays of quantum devices of this kind.

2. Electrical transport through Single molecules in nanoscopic structures as detectors of nuclear spin dynamics; the use of this in quantum devices.

3. Quantum confinement in artificial structures produced by scanning tunneling manipulations of atoms and molecules on single crystal surfaces or by a combination of electron, ion, and focused x-ray beams. As in the quantum mirage-like studies, we can in this way image information being generated by atomic or molecular structures at a predetermined point distant from the actual source.

4. Control of solitonic-like domain wall motion in one-dimensional magnetic wires in half-metallic ferromagnets by electron transport. The study of conjugated organic molecular systems to control the motion and eventual storage of solitons in single (macro)molecular structures.

5. New materials for magnetoelectric effects in which small fields can be used to control large changes in electric or magnetic polarization. These are materials in which Berry phase issues together with time reversal symmetry breaking as well as inversion symmetry breaking join hands. The use of spin and rotational degeneracies and the Berry phase in certain molecules, to produce half-integer rotational excitations for new two-level systems. Such quantum mechanical rotations can persist even in the solid down to very low temperatures.

6. Fundamental studies of fractionalization in low dimensional systems such as spin charge separation, fractional charges, fractional spins excitations as in spinons. Fundamental studies of the excitations in quantum magnets in low dimensions (spin chains, 2-d quantum magnets), and also in higher-dimensional quantum magnets like solid He-3 or quantum spin glasses. Study of the spin dynamics in such systems, partly with an eye on quantum information processing and decoherence studies.

7. The production of very short pulsed very high magnetic fields with focused laser or X ray beams using the inverse Faraday effect. Such large fields could make magnetic recording and reading extremely fast and efficient increasing storage densities.

8. New materials based on theoretical design of nanostructures of selected materials, into new structures with exceptional properties. These are examples of new classes of systems which we believe will evolve from the new concepts based on building blocks whose properties are determined by the surroundings via quantum mechanical tunneling, confinement and interference. The use of molecular beam epitaxy and focused ion beam methods etc to produce structures that cannot be made with standard solid state chemistry methods.

9. New molecular like structures based on defects in semiconductors and insulators with particular topologies, which theoretically can exhibit spectacular magnetic properties purely because of symmetry, quantum mechanics, and the nature of Fermions (Pauli principle). “Molecules“ can be made in this way, which could not be realized without the semiconducting background these structures are in.

10. Organic and biomolecular systems in photovoltaic devices such as batteries and solar cells utilizing apparent large length scale disipationless transport of charge and excitations. A basic understanding of these large length scale effects as in DNA for example or photochemistry is still missing. A study of model systems combined with theory of complex systems should provide some answers.

11. Spintronics, i.e., the manipulation of spin without the movement of charge, as in the spin Hall effect, magnetic semiconductors and half metallic ferromagnets. The development of ‘quantum spintronics’ in which the quantum phase of the spins is being manipulated. The combined theoretical and experimental development of spin-based quantum information processing systems, involving spin qubits.

NB: these items do not yet include input from the foreign institutions

C. Infrastructure Description and Total Budget

As a result of developments over the last ten years in materials science, nanofabrication and in the theoretical understanding of quantum phenomena in correlated electron systems, it is now an opportune time to establish a program to create the new quantum technology. The team assembled at UBC spans a wide range of expertise in the growth of materials ranging from III-V semiconductors to complex transition metal oxides. Experience in nanofabrication spans bottom-up approaches such as molecular self-assembly and top-down fabrication of device structures such as quantum dots and photonic crystals.

This present team, the international partners and the new faculty to be hired in related areas of materials science and technology all needs a suite of tool that will support many years of highly innovative and collaborative advanced materials projects. The infrastructure at UBC that greatly expands this group’s scope for quantum materials and devices will be integrated in a way that enables novel approaches to materials problems and synergy between the team members. The centre of the new infrastructure will be a facility for the growth and characterization of oxide thin films, heterostructures and devices using molecular beam epitaxy (MBE). This complements existing materials capability at UBC and throughout the collaboration, and provides a unique approach to gaining atomic control of complex materials by adapting techniques that were developed for semiconductors. The novel arrangement of the facility will be to array a suite of tools around the MBE to study and characterize the materials and then fabricate devices that exploit the new materials’ properties. Some tools will be integrated right into the main chamber for in situ study of the materials as they grow. Other capabilities will lie in ancillary chambers that can either stand alone or directly connect to the MBE, allowing the flexibility to use them independently or to integrate them into a seamless fabrication sequence when needed. This will include tools essential for device fabrication, such as a focused ion beam, e-beam lithography and thermal and e-beam evaporators for depositing high purity metal films and electrodes. Some tools must stand alone for technical reasons, but samples can be shuttled between them with a Liquid Helium cooled vacuum suitcase. These include a low temperature scanning tunneling microscope that requires an ultralow vibration environment to obtain electronic spectra of surfaces with atomic resolution. Also in this class of experiment is Angle-resolved photoemission performed at a beamline at the Canadian Light Source (CLS).

This core facility requires supporting infrastructure. Floating zone image furnaces will be used to grow bulk single crystals of oxides, both to complement the film growth and to provide novel, high purity substrates for the films and devices. A state-of-the-art Electron Microscope allows imaging down to a few nanometres, while a Time-of-Flight Ion Scattering Spectrometer and X-ray scattering apparatus help identify the chemistry and structure of surfaces. A High-Field Magneto-Transport System will provide a flexible and user-friendly platform for studying electronic, physical and optical properties of materials and the devices that are fabricated from them. Many of the apparatus are seeking unusual quantum phenomena that occur on small length scales are visible only at low temperatures, so a Helium liquifier will be essential.

The new infrastructure required at UBC to fulfill these goals will include:

1. Modern facilities for materials and device production and characterization

state of the art Oxide multiple source MBE	$ 5 million
High resolution electron microscopy with high resolution electron energy loss GATAN	$ 10 million
High resolution and high energy synchrotron based electron spectroscopy	$ 5 million
Low temperature STM	$ 2 million
Electron beam lithography	$ 4 million
PPMS system for electrical , magnetic optical and optoelectronic characterization	$ 1.5 million
Crystal growth equipment	$ 1.5 million
Small spot XPS including Auger, monochromatized source, multiple source	$ 2 million
Clean room device fabrication and characterization equipment.	$ 2 million
FIB dual beam system	$ 2 million
TOF SIMS	$ 2 million
Computational facilities	$1 million
Equipment Total	$39 million

2. An extension to the AMPEL building, to house new infrastructure and personnel $ 25 million

3. Roughly 5 new faculty slots to cover white spots not covered by us or the international partners at this time. especially at the interface between biology, Physics and Engineering; solid state Chemistry, Physics and sustainable energy; Physics, Engineering, and Medicine; use of modern large facilities such as synchrotrons, free electron lasers, neutrons in the studies of complex systems. etc

4. Support for technical staff to operate central facilities such as clean room, surface analysis, electron microscopy, electron beam lithography, materials characterization, MBE and ultra-thin film preparation facilities ----

5. A general operating fund of $ 8.5 million p.a.

We propose to supplement the $35 million CFI funding with $30 million BC provincial funding for the initial investment and a further $8.5 million per year initially for 5 years in operating costs covered by UBC and the BC provincial government sources, as well as user fees from national and international sources. We emphasize here that these sums do NOT include funding to be raised by the international partners for complementary facilities in Australia and the USA.