Research Activities in Physics at McGill University
Cover image: A Star-Bursting Filament (from the group of Prof. Tracy Webb). The Herschel Space Observatory has discovered a giant, galaxy-packed filament ablaze with billions of new stars. The filament connects two clusters of galaxies that, along with a third cluster, will smash together in several billion years and give rise to one of the largest galaxy superclusters in the universe. The three galaxy clusters of the emerging supercluster, known as RCS2319, are seen in visible and X-ray light. Observations by Herschel in infrared light are super-imposed, with bright, colored regions indicating greater infrared emissions. A white circle broadly outlines the 8 million light-year-long intergalactic filament. In visible light, the filament does not stand out because dust obscures the star-formation activity in distant galaxies. Telescopes like Herschel, however, can detect the infrared glow of this dust as it is heated by newborn stars. Image credit: ESA/NASA/JPL-Caltech/CXC/McGill Univ.
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Introduction

A Word of Welcome

The McGill Department of Physics has a long tradition of frontier research dating from the historic experiments done here by Rutherford more than a century ago. One hallmark of our modern Department is a diversification into many areas: students pursuing graduate studies here have a wide spectrum of cutting-edge research activities from which to choose in a congenial yet challenging environment, driven by a young and active faculty.

This brochure familiarizes prospective graduate students with the many facets of the Department, providing short descriptions of research activities organized by the research groups and also around particular researchers. For information on our graduate program, including how to apply, fees and financial support, degree requirements and graduate courses offered, please see our webpages at http://www.physics.mcgill.ca/grads/ for the most up-to-date information.

The Department is based in the Rutherford Physics Building, a modern building where most of our on-site research is performed, situated on the scenic and pleasant McGill campus in the heart of downtown Montreal, a lively city with many attractions.

I hope you consider the McGill Department of Physics for your graduate studies.

Peter Grütter, Chair of the Department and James McGill Professor
The Challenge of Physics

Physics is the fundamental science. Its goal is no less ambitious than to discover and understand the laws that govern everything in the Universe, from the behavior of the smallest building blocks of matter to the structure of the space-time and the Universe itself. Given all the wonderful variety of phenomena in the Universe, it is truly remarkable that human beings could conceive that such a goal is even possible.

The discovery of relativity and quantum mechanics in the 20th century gave us, for the first time in history, the hope that this goal may be achievable. Today, we have a spectacularly successful theory called the 'Standard Model' which together with the general theory of relativity provides the physical laws that govern all phenomena known to human beings so far. Does this mean everything can be understood by the Standard Model? The answer is, of course, no.

First of all, the phenomena we have been able to observe and study are a tiny fraction of our Universe. Just as Newtonian mechanics gave way to quantum mechanics, our current understanding should give way to a new understanding where discoveries at the frontiers of physics demand so. Second, knowing the microscopic laws of physics does not mean that one understands all the macroscopic phenomena. There are unending varieties of surprises in nature such as how a cell functions or how materials at extreme temperatures behave that await further understanding.

Therefore a physicist, regardless of specialty, is someone who is excited by these daily challenges: How do I find new phenomena? How do I understand the new phenomena? How do I improve current theories and techniques to do so? How do they all fit together?

At McGill, Professors and graduate students meet these challenges daily with great enthusiasm. In condensed matter physics, we push the envelope of what materials can do. A new field of 'soft matter physics' is also emerging strongly at McGill. In nuclear physics, McGill physicists are helping to re-create and study a new state of matter called quark-gluon plasma, which only existed during the first few micro-seconds after the Big Bang. Some of our particle physicists are in the hot pursuit of the superstrings and extra-dimensions. Observations of astronomical objects with ground and space-based telescopes allow our astrophysicists to probe extreme physical conditions difficult or impossible to study in the laboratory.

The exploration of the frontiers of physics is not just for intellectual fulfillment. Major life-changing discoveries and developments in technology were made by physicists. These include the transistor and the laser, the two most important ingredients of modern information technology. In addition, physics has a tradition of expanding its domain of activity into new areas where our unique viewpoint - our ability to identify universal features of a problem, beyond the specifics of the problem in question - is of great value. In particular, condensed-matter research has served as the bridge from physics to other sciences, such as biology, chemistry, and engineering.

These are just some of the areas in which physicists are trained during their graduate studies at McGill. Descriptions of different research programs are given later in this brochure.
Rutherford's Legacy

Physics at McGill University has a long history, perhaps most famously dating back to Ernest Rutherford at the beginning of the twentieth century. In the autumn of 1898 Rutherford was appointed Macdonald Professor of Experimental Physics at McGill University. At this time the Department of Physics (strictly speaking, the Physics Laboratory) comprised two professors, and a small number of junior instructors and research students. There was a fairly heavy teaching load, mainly to students of engineering, medicine, chemistry and other disciplines rather than physics per se. The vacancy arose from the resignation of Professor Hugh Callendar, who decided to return to the UK. The Chairman of the Department, Professor John Cox, went over to Cambridge to seek a replacement, and J.J. Thomson recommended Rutherford.

Rutherford's research at McGill covered every aspect of radioactivity, including the nature and properties of the 'emanation' (radon) produced by radium and thorium, the heating and ionization properties of the radiations, the charge and nature of the alpha, beta and gamma rays, excited radioactivity, and elucidation of the three natural radioactive series (uranium-radium, actinium and thorium). During his nine years at McGill, Rutherford published 69 papers, either alone or with a second author. The latter group included graduate students, demonstrators and professors at McGill and (after 1903) graduate students and post-doctoral scientists from several countries outside Canada. These collaborators published some 30 independent papers on various aspects of radioactivity, mostly on topics suggested by Rutherford and under his general guidance.

The most significant collaboration was between Rutherford and Frederick Soddy, a young English chemist who was appointed Demonstrator in Chemistry at McGill in 1900. The collaboration between Rutherford and Soddy lasted only 18 months, from October 1901 to March 1903, but resulted in nine important papers, including "The cause and nature of radioactivity," published in two parts in 1902. Other than Soddy, the most important of Rutherford's collaborators were Arthur Stewart Eve, an English physicist; Howard Barnes, a young Montreal physicist; Howard Bronson, an American physicist from Yale; Tadeusz Godlewski, a physical chemist from Cracow (Poland); and Otto Hahn and Max Levin, both physical chemists from Germany.

Rutherford moved from Montreal to Manchester in the summer of 1907, and the following year he was awarded the Nobel Prize in Chemistry for "researches on the disintegration of the elements and the chemistry of radioactive matter." Although he was no longer in Montreal, most of the work referred to in this citation had been carried out during his 9-year tenure at McGill. Rutherford delivered his Nobel Lecture in Stockholm on December 11, 1908, under the title, "The Chemical Nature of the alpha-Particle from Radioactive Substances."

As arguably the premiere experimental physicist of the 20th century, Rutherford's work affected not only the development of modern physics in general, but also profoundly influenced the history of mankind.

With that exceptional start, McGill's Department of Physics has established itself as one of the major institutions in North America.

In 1976, the Department moved from the Macdonald building into a new building which bears the name “Ernest Rutherford” in honour of Rutherford's illustrious contribution to science while at McGill.

In November 2009, the Historic Sites Committee of the American Physical Society offered plaques (one in English and one in French) commemorating the seminal work done at McGill by Rutherford and Soddy. The plaques are installed in the entrance of the Schulich Library of Science and Engineering (the former Macdonald Physics Building).
Research Activities

Owing to its many research groups, the research activities in the Department of Physics are as diverse as they are exciting. In terms of length scale, our researches cover attometers to billions of light years. In terms of energy scale, our researches range from micro-kelvin to the Planck energy. In any given week, there are usually 4 to 5 seminars and there is regular Physical Society Colloquium series (first established by Rutherford). The Department also has a close relation with the Medical Physics Unit.

The activities of the different research groups are described in the following pages. More information can be also found at [http://www.physics.mcgill.ca](http://www.physics.mcgill.ca), or the web pages of individual professors. Note that there is often significant overlap and collaboration between the different groups, and individual faculty members research activities can span more than one research area, e.g. biophysics/condensed matter or astrophysics/high energy theory.

## Faculty’s Main Research Areas

### Astrophysics

  - A. Cumming

- **Experimental Cosmology, Cosmic Microwave Background, Astro-particle Physics**
  - M. Dobbs

- **Cosmology, Cosmic Microwave Background, Gravitational Lensing**
  - G. Holder

  - V. Kaspi

- **Neutron Stars, X-ray Binaries, Gamma-Ray Bursts, Pulsars, X-ray Astronomy, Ultra-Cool Dwarfs, Time Series Analysis**
  - R. Rutledge

- **Galaxy formation and evolution, star-burst and infrared galaxies, galaxy clusters**
  - T. Webb

### Biophysics

- **Gene Networks Dynamics, Systems Biology, in Silico Evolution, Physics of the Embryo**
  - P. Francois

- **Single-molecule spectroscopy, Fast molecular search processes, Confinement physics**
  - S. Leslie

- **Nanofluidics, Nanoconfined Polymers, Single Bio-molecule Detection and Manipulation**
  - W. Reisner
Cellular Biophysics, Image Correlation Spectroscopy, Fluorescence and Nonlinear Microscopy, Technique Development

Condensed Matter Experiment

Metallic Multilayers, GMR, Supermagnets, Glassy Metals, Magnetocaloric Materials

Quantum optics, defect-based spin systems, magnetic sensing, quantum information science

Low-Energy Ultrafast Phenomena in Condensed Matter, Ultrafast Terahertz Spectroscopy, Conductivity of Disordered Materials, THz Wave Photonics, Nonlinear THz Interactions

Ultra-Low Temperatures, Nanoscale Physics, Novel NMR Methods, Confined Electrons, Fractional Quantum Hall Physics, Device Prototyping

Nanoscience, Nanotechnology, Scanning Probe Microscopy

Low Dimensional Systems and Quantum Structures, Superconductors, Quantum Computing

Mössbauer spectroscopy, Frustrated Spin Systems, Neutron Scattering, μSR, Magnetic Materials

Optomechanics, Quantum Motion, Sensing, Photonics, Nanotechnology

Transient structures of molecules and materials, Ultrafast electron diffraction and imaging, Ultrafast laser spectroscopy, Nanocomposite and functional materials

X-ray Diffraction, Non-equilibrium Structures

Condensed Matter Theory

Mesoscopic Systems (Noise and Transport), Quantum Computation, Nanoelectromechanical systems

Quantum Information Processing, Quantum Dynamics, Nanoscale Nuclear Magnetism

Non-equilibrium Structures

Nanoelectronics Theory, Ab-initio Modeling, Soft Matter

P. Wiseman

Z. Altounian

L. Childress

D. Cooke

G. Gervais

P. Grutter

M. Hilke

D. Ryan

J. Sankey

B. Siwick

M. Sutton

A. Clerk

W. Coish

M. Grant

H. Guo
Strongly Correlated Electron Systems, Unconventional Superconductivity, Topological Insulators, Graphene

T. Pereg-Barnea

Computational Materials Science, Non-Equilibrium Phase Transformations, Phase Field Molding, Solidification, Dendritic Growth, Solid State Transformations, Reaction-Diffusion Equations, Flame Fronts

N. Provatas

**High Energy Experiment**

Deep Inelastic Scattering, Photoproduction, Particle Jets, Proton and Photon Structures, ZEUS

F. Corriveau

BaBar, B Physics, rare B decays

S. Robertson

Top Quark, Physics Beyond the Standard Model, DZero and ATLAS Experiment, Trigger System

B. Vachon

Heavy-Quark Production, Higgs Searches, New Phenomena, ATLAS, CDF, and SuperB

A. Warburton

**High Energy Theory**

Inflationary Cosmology, Theory of Cosmological Perturbations, Superstring Cosmology, Baryogenesis

R. Brandenberger

Particle Physics and Cosmology

J. Cline

String Cosmology, Superstring Theory, Quantum Field Theory, Mathematical Physics

K. Dasgupta

String Theory, Cosmology, and Black Holes

A. Maloney

Thermal Quantum Field Theory

G. Moore

Mathematical Physics, String Theory, Algebraic Geometry

J. Walcher

**Nonlinear and Atmospheric Physics**

Non-linear Variability in Geophysics

S. Lovejoy
Nuclear Theory

Heavy-ion Collisions
Relativistic Heavy-ion Collisions
Relativistic Heavy-ion Collisions

Nuclear Experiment

Heavy-ion collisions
Spectroscopy of Exotic Nuclear Isotopes
Spectroscopy of Exotic Nuclear Isotopes

Particle Astrophysics

Ground-based Gamma-ray Astrophysics
Ground-based Gamma-ray Astrophysics

S. Das Gupta
C. Gale
S. Jeon
J. Barrette
F. Buchinger
J. Crawford
D. Hanna
K. Ragan
This is a fascinating time in astrophysics, with new observational capabilities offer us a more detailed view of the universe and its constituents than ever before. McGill’s Astrophysics group works at the forefront of a wide variety of major astrophysical research areas, including neutron stars, pulsars, magnetars, pulsar wind nebulae, X-ray binaries, thermonuclear bursts, black holes, gamma ray bursts, active galactic nuclei, galaxy evolution, galaxy clusters, microwave background, cosmology and exoplanets.

Neutron stars and pulsars (Cumming, Kaspi, Rutledge)

The existence of neutron stars was predicted in the 1930s, more than 30 years before the first discovery of radio pulses from pulsar PSR B1919+21, in 1967. In the past 40 years new telescopes, instruments and detection methods have resulted in the discovery of nearly 2000 neutron stars. They can be observed in many wavebands, notably radio, X-rays and gamma-rays and are grouped into various categories including pulsars, magnetars, radio rotating transients, X-ray dim isolated neutron stars, and neutron star X-ray binaries.

The McGill Neutron Star and Pulsar group studies a diverse range of subjects in observational pulsar physics, using data from many of the world’s most powerful observatories and satellites, including Chandra, XMM-Newton, Swift, and the new mission NuSTAR launched in 2012. We study interesting individual systems such as double pulsars, magnetars, low mass X-ray binaries and supernova remnants, as well as the distant and enigmatic gamma-ray bursts. We are also involved in large-scale surveys to discover new pulsars using large radio telescopes, including Arecibo and the Green Bank Telescope.

The McGill Neutron Star theorists are interested in the fundamental structure of neutron stars. We investigate the origin and evolution of their spin and magnetism, their interior structure, and the properties of neutron star binary systems.

Experimental Astrophysics (Dobbs, Hanna, Ragan)

The experimental astrophysicists at McGill contribute to the building of observational facilities to explore various energy bands in astronomy. Our high-energy research is carried out with the VERITAS observatory in Arizona, which is sensitive to gamma rays with energies from 100 GeV to over 30 TeV.

We also have an active cosmology instrumentation lab that has developed important components for cosmic microwave background detectors such as the South Pole Telescope and the balloon-borne polarimeter EBEX. Key components of the proposed CHIME hydrogen mapping experiment will be developed at McGill.
Galaxies and Cosmology (Dobbs, Holder, Webb)

The Galaxies and Cosmology group at McGill includes observers, theorists and experimentalists studying the evolution of galaxies, clusters of galaxies and the cosmic microwave background in order to understand the processes by which our Universe formed and evolved.

McGill is involved in numerous CMB experiments. One of these experiments is the South Pole Telescope (SPT), which is surveying the CMB for shadows of galaxy clusters: the largest gravitationally bound objects in the universe. The detection and characterization of these galaxy clusters allows us to probe structure formation, cosmological parameters and the equation of state of dark energy: an enigmatic substance driving the accelerated expansion of our universe.

The cosmology instrumentation lab at McGill has developed important components for the South Pole Telescope and other CMB experiments such as the balloon-borne polarimeter, EBEX. Key components of the proposed CHIME hydrogen mapping experiment will be developed at McGill.

Our observational cosmologists use world-class telescopes such as Gemini, the Spitzer Space Telescope and the Very Large Array to look back in time and investigate the detailed physics of galaxy evolution. We are interested in the processes which build the stellar mass of galaxies, feed the supermassive black-holes at their centers, and group them into the structures and shapes we see around us today.

Exoplanets (Cumming)

A tremendous number of different kinds of observations of exoplanets are now available, including statistical distributions of planet properties and orbits, the surface temperature profiles of hot jupiters, and even the obliquities of their orbits. The numbers will continue to grow over the next few years, including new samples of exoplanets such as those from direct-detection surveys. These observations offer an opportunity to answer basic questions about planet formation and the physical processes occurring in exoplanet interiors.

At McGill, we are working on two aspects of exoplanets. The first is the statistical properties of the sample of exoplanets, which have a lot to tell us about the physics of planet formation. Part of this work involves applying Bayesian techniques to the detection of planetary orbits and constraining properties of the planet population.

Second, we are engaged in a number of studies of the physics of gas giant planets, with projects including ohmic heating as a way to inflate some of the hot jupiters, the early evolution of young gas giant planets, and how we can use observations of directly-detected gas giants to constrain the formation process and their internal properties.
My work is in the area of theoretical astrophysics, in particular studies of neutron stars and exoplanets. Neutron stars contain matter that is compressed to a density greater than an atomic nucleus and initially heated to temperatures of more than a billion degrees. They have a surface gravity one hundred billion times larger than the gravity on Earth, and magnetic fields vastly greater than the strongest laboratory magnets. They therefore give us a unique chance to study material under extreme conditions of density, temperature, gravity, and magnetic fields.

The study of exoplanets is a new and rapidly growing part of astrophysics, with over three hundred planets now known to be orbiting nearby stars. The surprising diversity of these planetary systems has led us to rethink our ideas of how planets form and evolve.

We take a theoretical approach to these problems, with the aim of learning about the underlying physics by comparing to observations. Research in exoplanets at McGill ranges from studying the statistical distributions of extrasolar planet properties and what they have to tell us about planet formation, to the physics of exoplanet atmospheres. Recent projects on neutron stars include understanding thermonuclear explosions in their surface layers, the origin and evolution of their magnetic fields, and the physical properties of their solid crusts. These are fascinating problems which involve a range of different physics, including magnetized fluids, nuclear physics, condensed matter physics, radiation transport, and electrodynamics.

**Recent Publications**


The Keck Planet Search: Detectability and the Minimum Mass and Orbital Period Distribution of Extrasolar Planets, A.
Matt Dobbs

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Matt is a hands-on experimentalist designing, building and using observational cosmology experiments to better understand the origin, fate, and composition of the universe. His main focus today is the Cosmic Microwave background.

Although the interactions of matter at energies accessible at present-day particle colliders (where gravity is negligible) are well understood in the framework of Particle Physics, we find a mammoth deficiency in our appreciation of nature when we apply these laws at cosmological scales: only 5% of the energy density in the universe can be ascribed to the known matter constituents. About 25% is wrapped up in mysterious dark matter (which couples only to gravity) and the remaining 70% appears to be in the form of dark energy, a recently discovered contribution which is pushing the universe to expand faster as time goes on.

I am an experimental physicist interested in understanding how matter and its interactions evolve from the early universe to create the cosmology in which we live today. Broadly speaking, the Big Bang model is consistent with astronomical observations and experimental measurements as long as the theory includes an early period of Inflation (when the universe expands faster than the speed of light). Inflation predicts other signatures such as a gravity wave background emanating from the inflationary era that may be encoded in the observable universe.

The signature of inflationary gravity waves may manifest itself as an observable polarization pattern in the Cosmic Microwave Background (CMB) radiation, providing a rare opportunity to probe nature at the inflationary energy scale where all the fundamental forces are important. I am involved in the construction of an experiment in California’s White Mountains, called POLARBEAR, to probe this signature. Two other experiments, APEX-SZ (deployed to the Atacama Plateau in Chile) and the South Pole Telescope, will use a subtle distortion of the CMB from galaxy clusters called the Sunyaev-Zel'dovich effect to measure the expansion history of the universe and gain new information about Dark Energy.

Student Opportunities: Students engaged in these experiments will gain a knowledge of cosmology, low noise electronics instrumentation, cryogenic sensors and detectors, and data analysis. Travel to the experimental sites (White Mountains, Atacama Plateau, or the South Pole) is expected.

Recent Publications


Observational cosmology has made tremendous advances over the last few years, ranging from the discovery of the accelerating universe, driven by dark energy, to the characterization of the fluctuations in the microwave background to very high precision. The observed situation in the universe is a curious one, however, with 70% of the universe in the form of dark energy, 25% in the form of dark matter, and only 5% in the form of baryonic matter. Both dark energy and dark matter have direct ties to particle physics, so astrophysics can make important contributions to physics through a better understanding of the nature of the dark matter and the properties of dark energy.

My research is built around theoretical studies of how astrophysics and observational cosmology can experimentally determine the most important properties of dark matter and dark energy. The observational probes that I have investigated are the cosmic microwave background and gravitational lensing, and there are several experimental projects coming up that show great promise. Among others, upcoming projects of interest include the Atacama Large Millimeter Array (an international, including Canada, enterprise), the South Pole Telescope, and the Square Kilometer Array.

I am always interested in new graduate students, with projects ranging from timescales of a few months to several years, with the topics including gravitational lensing, large scale structure in the universe, the cosmic microwave background, the first stars, and in general any astrophysics that has important ramifications for observational cosmology (e.g., star-forming galaxies and black holes in galaxies).
More massive than our Sun, yet packed into a sphere the size of Montreal (and sometimes spinning faster than your kitchen blender!), neutron stars represent the most extreme form of non-singular matter in the known Universe. Emitting beams of radiation from their magnetic poles, these objects are often observed via their pulses, like cosmic lighthouses. My research involves the observational study of a variety of types of neutron star, using primarily radio and X-ray observations. The main goal of my research is to use neutron stars to understand exotic physics inaccessible to Terrestrial laboratories. Such physics includes Einstein’s theory of General Relativity, the nature of matter at supranuclear densities, and the behavior of matter in extreme magnetic fields. I am also interested in astrophysical topics surrounding neutron stars, especially understanding the different observational manifestations of these objects and their implications for the physics of core collapse supernovae and stellar evolution.

Specifically, I am currently leading or involved in several different research projects, including: searching for radio pulsars using the 100-m Green Bank radio telescope in West Virginia, and the 305-m Arecibo radio telescope in Puerto Rico as part of international consortia; detailed radio study of a variety of interesting binary radio pulsars; long-term monitoring of magnetars using NASA’s Swift satellite; studying high-magnetic field radio pulsars, magnetars, and pulsar wind nebulae using NASA’s Chandra X-ray Observatory and ESA’s XMM-Newton Telescope, and a variety of smaller projects. I am also Coordinator of the the Galactic Science Team for the recently launched NASA mission NuSTAR, the first focussing hard X-ray telescope.
Prof. Robert Rutledge is an observational astronomer who studies neutron stars and black holes. His primary interest is in measuring the sizes of neutron stars, using X-ray spectroscopic observatories such as NASA's Chandra X-ray Observatory and ESA's X-ray Multi-Mirror Telescope. Measuring the sizes of neutron stars provides direct measurements of strong-force physics, since the size of a neutron star is determined by strong-force interaction of matter at and above nuclear density. He also studies the phenomena which neutron stars and black holes share - in particular, their accretion and intensity fluctuations - as well as the phenomena which set them apart, most obviously the absence of a material surface in black hole systems, or the presence of strong magnetic fields in neutron star systems.

Additional interests include: gamma-ray bursts; coronally active low-mass stars; X-ray binaries, and transients; millisecond X-ray pulsar timing; optical identifications of astronomical X-ray sources.
My research focuses on the formation and evolution of galaxies, and massive galaxies in particular. I study these processes by gathering observational data using some of the world’s most powerful telescopes. Recently, we discovered a new population of galaxies which appear to represent an explosive phase of massive galaxy formation in the early universe. These objects are so deeply enshrouded in dust that they are almost undetectable at optical wavelengths even with today’s largest telescopes. Dust, small grains of carbon and silicon in the interstellar medium, absorbs optical and ultraviolet light, thereby either modifying the radiation emitted by objects behind the dust, or blocking it completely. It now seems clear that dust absorption is important during almost all phases of galaxy evolution and a comprehensive study of the relevant physics requires observations at longer wavelengths, such as the far-infrared where the dust emits energy or at radio wavelengths, which penetrate through the dust shield. In fact, any complete understanding of galaxy formation requires information at all wavelengths, from the X-ray to the radio. Using telescopes such as the James Clerk Maxwell submillimeter telescope, the Spitzer infrared space satellite, the Very Large radio array, and the Gemini optical/infrared telescope I am investigating questions such as: what are the important timescales for galaxy formation - i.e. do massive galaxies form most of their stars in a single burst or gradually over time; what effect does feedback from central black holes have on star formation; what role does galaxy-galaxy merging and high-density environments, play in driving the evolution of galaxies.

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Astrophysics
We know far more about the inner workings of stars than we do about the inner workings of a cell, yet the mechanisms of a cell are far more complex (for an introduction, see Alberts, Molecular Biology of the Cell, 5th Edition, Taylor & Francis, 2007). Physics offers a unique set of perspectives from which to tackle this problem and attempt to find general organizing principles applicable to all biological cells. Our biophysics groups are interested in characterizing complex networks that govern essential cellular processes such as the ability to sense, transmit, and generate signals. For example, the physical network of the cell comprises a mechanical system that can gain sensory information, and transmit and generate forces to orchestrate the migration (see Wiseman; Grant). Cell membranes mediate the inputs to this network through adhesion at surfaces (Wiseman), through their intrinsic mechanical properties (Grütter), and via mechanosensitive gating (Wiseman). Biomolecular networks regulate these physical networks by integrating chemical signals and controlling gene expression and may be modeled using nonlinear dynamics (François, Grant). In addition, biophysics research at McGill focuses on development of new technologies to probe the cell at the single-molecule level, including development of nanofluidic bioanalysis and biomnipulation technologies for whole genome and epigenetic analysis (Reisner).

As well there are collaborations that involve studies in fields related to neuroscience, such as synaptic formation and neuron migration (Grütter and Wiseman; Neurophysics Training Grant Program and Neuroengineering); and to mechanosensing, such as sensors to measure molecular motor systems (Grütter and collaborators at the Meakins Christie Chest Hospital and the Bone Centre; Rassier, Kinesiology, associate member in Physics), or to developmental biology such as embryonic growth and patterning (François and Pourqui group at the IGBMC Strasbourg, France).

Students and postdoctoral researchers trained in this environment gain quantitative and interdisciplinary skills, and can come from biological or physics backgrounds. Our biophysics research programs offer students and postdoctoral researchers the opportunity to gain expertise in state-of-the-art two-photon and nonlinear microscopy, image correlation spectroscopy and other fluctuation-based methods, direct tracking in live cell methods, confocal...
microscopy, computational biology, lasers and optical trapping, atomic force microscopy, protein-engineering, signal transduction, gene expression, neurophysiology, micro/nanofluidic bioanalysis device fabrication, nanoparticle labels, and total internal reflection and fluorescence resonance energy transfer microscopies.

Characteristic configurations of a protein in cold water ($T=0.15$ and $T=0.17$), at an intermediate temperature ($T=0.21$), and in hot water ($T=0.25$). The distance of highlighted (shell) water molecules to the protein is less than 2.5 in units of Rh. In cold water, the monomers are typically surrounded by clathrate-like cages.

Velocity map of retrograde transport of alpha-actinin/EGFP in a mouse fibroblast cell. Measured by STICS analysis.
How does an immune cells recognize antigens? How does an embryo develop? These deep biological questions can not be answered without taking into account the emerging dynamics of gene networks within cells and of cells within tissues. The François group develops mathematical and numerical tools directly inspired by physics to describe and understand these dynamics. For instance, we try to figure out if cell movements within a tissue can be modeled as a simplified out of equilibrium stochastic process, and if formation of “structures” within an embryo (such as a vertebrae) can be described using a phenomenological dynamical system approach.

We work in close collaboration with experimentalists in McGill University and in foreign universities, developing both models and methods (image analysis) to quantitatively describe biological dynamics.

We are also interested in developing physics-inspired models of evolution. Is Darwinian evolution similar to energy minimization of physics? If so, can we “predict” what kind of networks can evolve? We have applied successfully these ideas to a variety of problems ranging from circadian oscillations to definition of cellular identities.

Recent Publications


Maintaining a multidisciplinary approach, the Leslie Lab aims to address unanswered questions about molecular transport in complex biophysical environments. We are fascinated by how molecules move about and perform myriad functions. On the scale of the cell nucleus - how can a DNA-binding protein find its target site so rapidly in such a crowded environment? On the scale of the body - how does an adrenaline shot take its effect in a matter of seconds?

By employing a suite of sensitive microscopy techniques, including the CLIC microscopy technique that Dr. Leslie developed as a postdoctoral researcher, we will tackle a range of compelling questions about molecular transport in complex biophysical systems.

In particular we study:

- Protein-DNA search problem
- Homologous recombination: a DNA-DNA search problem
- Molecular dynamics, squished and squeezed
- Convex Lens Induced Confinement: a Simpler Way to Spy on Rogue Molecules (Paper) (Technology Review Article)
In Walter Reisner’s upcoming bionanofluidics lab at McGill University one of our projects will be to explore how complex sub micron nanotopographies embedded in a confined slit-like nanochannel can be used to perform manipulations of single biopolymers, such as DNA, in solution. Variation in local confinement across the nanotopography results in spatial variation of a molecule’s configurational freedom, or entropy. Consequently, by controlling device geometry, we can create a user-defined free energy landscape that allows us to ‘sculpt’ the equilibrium configuration of a molecule. For example, nanogrooves embedded in the slit will extend DNA, unscrolling the genome for optical mapping. Individual square depressions, or nanopits, can be used to trap DNA at specific points in the slit. Arrays of nanopits will lead to complex ‘digitized’ conformations with a single molecule linking a number of pits (possibly the basis for a self-organized nanoelectronic circuit). The effect arises purely from design of device topography so there is no need for performing local surface chemistry. Moreover, in contrast to manipulation techniques based on optical tweezers or atomic force microscopy, we can manipulate many molecules in parallel without the need for complex instrumentation or attaching beads/chemical linkers to the molecules.

Recent Publications

My research interests lie at the interface between the physical and biological sciences. I am interested in understanding the molecular mechanisms involved in cellular adhesion (how biological cells stick together and to an underlying substrate) and how cells dynamically regulate adhesion receptors to control cellular migration. I am also interested in developing new biophysical methods such as third harmonic generation (THG) microscopy and the use of bioconjugated quantum dots as robust luminescent labels for biophysical imaging applications on live cells and neurons. Other projects will make use of an atomic force microscope (AFM)/total internal reflection fluorescence (TIRF) microscope that was built in collaboration with Prof. P. Grütter. My research topics include:

- Biophysical chemistry with emphasis on measuring macromolecular interactions in living cells using single photon and two-photon variants of image correlation spectroscopy (ICS) and image cross-correlation spectroscopy (ICCS)

- Live cell measurement of macromolecular dynamics and clustering phenomena of green fluorescent protein (GFP) integrin constructs to study their role in assembly of cell adhesion structures and in receptor ‘cross-talk’ with other signaling systems in cells.

- Development of new microscopic techniques that extend the capabilities of the ICS and ICCS methods. Development of a combined ICS, ICCS and imaging fluorescence resonance energy transfer microscopy. Applications of nonlinear harmonic microscopy and ICS to measurements of macromolecular mobilities in live cell systems. Application of bio-conjugated quantum dot labels for dynamic ICS measurements in living cells.

- Extension of ICS and ICCS for application to research problems in areas of neuroscience.

**Recent Publications**


**Awards**

Keith Laidler Award in Physical Chemistry (CSC) 2009
Fessenden Professorship in Science Innovation (McGill) 2008
Leo Yaffe Award for Excellence in Teaching McGill University 2007
Principal’s Prize for Excellence in Teaching (Assistant Professor Level) 2007
New discoveries are constantly made in condensed matter systems, be it in the form of new materials, such as graphene or magnetic superconductors, new quantum phases, such as strongly correlated systems or topological phases, new frontiers such as Terahertz or nanoscience, new paradigms, such as quantum computing or the mechanics of light. This is an exciting time for McGill’s condensed matter group, since its research groups are actively involved in these breakthroughs, providing an excellent opportunity for students to participate in this fascinating research area as detailed below.

Novel materials

Materials play a privileged role in condensed matter physics, since they often lead to new unexpected phenomena, such as unconventional superconductivity, quantum Hall effects, or new topologies. Researchers at McGill are interested in a wide range of materials including, carbon materials, such as diamond, graphene, buckyballs, and carbon nanotubes, topological materials such as topological insulators, superconductors and two dimensional electron gases, magnetic and spintronic materials, as well as biomaterials, including DNA. The focus is on the synthesis, the physical properties and characterization, as well as on the theory and large scale modeling of these novel materials.

A single crystal mono-layer dendritic graphene flake (graphlocon), grown on copper using chemical vapor deposition. The yellowish color is the graphene layer protecting the oxidized copper surface (reddish color) - Hilke group.

Fabrication and imaging of single atom deep pits in a NaCl surface - the individual Cl ions are visible in this ultra high vacuum AFM image (top row). These pits can be filled with molecules - the zoom at the bottom right shows the epitaxial structure of the PTCDA film on NaCl imaged by AFM - Grutter group.

THz spectroscopy at McGill - Cooke group.

A single crystal mono-layer dendritic graphene flake (graphlocon), grown on copper using chemical vapor deposition. The yellowish color is the graphene layer protecting the oxidized copper surface (reddish color) - Hilke group.

Extreme nonlinear optics

Trapping a THz photon with dynamic photonic structures

THz spectroscopy at McGill - Cooke group.
New frontiers

In research, pushing the boundaries ever further leads to new worlds opening up, be it at the ultra-short time scales such as those probed by femto-second pulses, or new frequency regimes, such as terahertz spectroscopy, or the fascinating world at the nano-scale, which can be made visible by local probes or with coherent X-rays and electron beams. At McGill these new frontiers are constantly pushed further with many groups active in these areas.

New paradigms

Quantum computing, which could change the way we think about information processing, has the potential to dramatically alter our information and communication technology. This goes further then pure quantum information processing, it also opens new directions in quantum detection schemes, the search for long coherence times in qubits, or also the interplay of light and matter in the quantum limit. McGill is actively involved in these new fascinating directions with extensive collaborations between theory and experiment.

(a) A scanning confocal image of high purity diamond shows fluorescence from individual nitrogen-vacancy (NV) defects (inset). (b) Nuclear magnetic resonance (left) and Rabi nutations (right) measured from a single nitrogen nuclear spin in diamond with long coherence times - Childress group.

Multi-scale simulation of a solidification front growing into a melt (top right). Several types of microstructures are shown. Bottom left: polycrystalline network of solid grains. Middle portions: coalesced dendritic branches. Top right: nucleation of dendritic crystals in liquid. Insets show zoom in of indicated regions, revealing the adaptive mesh of the simulation - Provatas group.

Pushing solid objects around with photons in an optical cavity - Sankey group.
My research interests are centered on metallic glasses, thin films, and magnetic materials.

Metallic glasses have physical properties distinctly different from those of the corresponding crystalline alloys, arising from the structure of the glassy state. Although glasses have no long range order they do possess short range order. The nature of the short range order depends on the composition as well as the relaxation state of the glass. We study the structure and relaxation using a combination of X-ray and neutron scattering techniques. Some of the physical properties that we study are electrical resistivity, spin-fluctuations, and superconductivity.

We manufacture thin films and magnetic multilayers using a multitarget DC and RF magnetron sputtering system. In particular we study films which consist of alternating layers of magnetic and non-magnetic metals which exhibit giant magnetoresistance and for small saturation fields, the films can be used as magnetoresistance sensors. Identifying simple multilayer systems with appropriate characteristics still remains a problem in this field. Apart from transport property measurements we use polarized neutron reflectometry and X-ray scattering techniques, both wide and small angle, to study the magnetic as well as the crystal structure of the multilayers and to characterize the interlayer roughness as well as the overall roughness.

Giant magnetocaloric materials (GMC) undergo a large change in magnetic entropy upon the application of a magnetic field. GMC materials that exhibit this effect near room temperature, are prime candidates for use as refrigerants in magnetic refrigeration. GMC is observed when a structural transition is coupled to a magnetic transition. We have studied R\textsubscript{5}M\textsubscript{4} compounds, where R is a rare-earth element and M is Si, Ge, or Sn. At present we are interested in other compounds that exhibit the GMC effect, such as Laves phases and LaFe\textsubscript{13} based compounds.

Zaven Altounian

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Our laboratory uses techniques developed in quantum optics and atomic physics to understand and control solid-state defect centers, while exploring their potential applications in quantum information science and metrology. These defects offer the exciting opportunity to combine narrow, atomic-like optical transitions with access to extraordinarily long-lived states of individual isolated nuclear spins in a robust solid-state device.

Our research focuses on the nitrogen-vacancy (NV) center, an optically-active defect in diamond. As in atomic systems, the electronic spin of the NV center can be optically pumped and measured with fluorescence detection, and its hyperfine interactions with proximal isotopic impurities allow access to single nuclear spins with coherence times measured in seconds even at room temperature. In many ways, the NV center resembles an ion wrapped in the diamond lattice. As a solid-state system, however, the NV center offers some advantages over the atomic systems it resembles. Electrodes can be defined tens of nanometers away from an NV center, enabling electron spin gates on nanosecond timescales or dynamic control of optical transition frequencies. Similarly, photonic structures can be fabricated into the high-index diamond crystal. The NV center and its proximal nuclear spins thus show great promise for combining long coherence times with fast control.

We are interested in using optically-active defects to gain control over individual nuclear spins and in particular to mediate interactions between them. One approach will explore techniques to use the optical transitions of the defects to connect nuclear spins separated by macroscopic distances; another examines magnetic interactions in nanoscale defect arrays. The critical idea is to identify and study interaction mechanisms that could be extended to large-scale networks, opening the possibility for meaningful applications in quantum information science. Intriguingly, these efforts may also be relevant to fundamental condensed matter physics and practical sensor devices: the same superposition states that underlie quantum information processing are also exquisitely sensitive to their surroundings, creating opportunities to study their mesoscopic environment and monitor external fields. Thus our second focus is on using these quantum-coherent devices to study fundamental physics and develop application-specific magnetic sensors.

Recent Publications


†Equal contributors.
Our lab focuses on ultrafast optical spectroscopy and photonics in the last portion of the electromagnetic spectrum to be controlled: the terahertz region between 0.3 and 30 THz. We use the intense short pulsed lasers to create phase-locked, single cycle bursts of light through a variety of nonlinear optical processes that are incredibly broadband, covering 7 octaves in frequency from 0.1 to >30 THz. Note that the entire visible spectrum spans only 1 octave! These extremely short pulses can then be used to take snapshots of charge carrier motion in materials on time scales that are not accessible by purely electronic means. Many solid-state systems contain a wide variety of excitations in the THz band, from phonon resonances to superconducting energy gaps. We can explore the dynamics of these fundamental excitations, and their interactions with one another, on sub-100 fs time scales where quantum mechanics comes into play.

Currently I am interested in conductivity dynamics in nanostructured semiconductors and conjugated polymers on extremely short time scales (sub-100 fs), the effects of Coulomb interactions on the transport properties of disordered materials, time-resolved nonlinear transport phenomena using high-field THz pulses, and developing new dynamic photonic components to control light in the THz spectral region.

The lab activities stretch from fundamental optical spectroscopy to the more applied development of THz sources and detection technology. We also have an active component of our research housed at the Advanced Laser Light Source (ALLS) facility in Varennes, Quebec just 20 minutes outside of Montreal. This facility houses a high-field THz pulse beamline where intense coherent field transients can be used to explore extreme light-matter interactions in a wide variety of materials.
In recent years, the electronic properties of low-dimensional structures such as electrons 'trapped' in quantum wells (2-D), flowing in a quantum wire (1-D) or forming a quantum dot (0-D), have drawn a high-level of interest for both fundamental aspects and promising device applications. As the temperature of the electrons present in these structures is reduced toward very near absolute zero, totally new properties emerge from a competition between many-body electron-electron interactions, disorder, and fluctuations. Examples of interest include 'bizarre' phenomena such as the fractionalization of charge excitations in 2-D, fractional (abelian and perhaps non-abelian) quantum statistics, as well as the separation of spin and charges predicted to occur in 1-D. These phenomena cannot be understood in terms of classical or Boltzmann physics; they are the result of the subtle mechanics that emerge when quantum particles interact near absolute zero temperature. Our group at McGill works at elucidating new quantum phases of matter in semiconductor electronic and fluidic structures fabricated 'on-a-chip'.

Material-wise, we use extremely low-disorder GaAs/AlGaAs grown in the highest-mobility Molecular Beam Epitaxy (MBE) facility in the World, as well as the cleanest material in Nature, 3He near T=0. We carry out measurements down to 8 mK, in high magnetic fields up to 16T. In our laboratory, we develop and implement novel tools and techniques such as resistively detected NMR with 'too few spins', scanned probe microscopy, as well as optical techniques. Starting from raw semiconducting material, we tailor-fabricate structures for electrons, or nanoholes for quantum fluids using cutting-edge clean room fabrication processes evolved from the nanotech community. In Gervais’ lab, the search for new quantum phases of matter occurs when the nanotech tools and low-temperature know-how connect with quantum physics.

Recent Publications


Positive and negative Coulomb drag in vertically-integrated one-dimensional quantum wires, D. Laroche, G. Gervais, M.P. Lilly and J.L. Reno, Nature Nanotechnology, 6, 793 - 797 (2011). (see also News and Views by Büttiker and Sánchez)


Figure: Vertically-integrated quantum circuit at the nanoscale. Layout and SEM picture of a vertically-integrated quantum circuit at the nanoscale, published in Nature Nanotechnology (see also News and Views by Büttiker and Sánchez). This work was done collaboratively between the Gervais’ group at McGill and the Center of Integrated Nanotechnologies at Sandia National Laboratories.
The Grutter group tries to push the limits of instrumentation and is one of the internationally leading groups in the development of atomic force microscopes (AFM) and its application to understanding how nanoscale objects can be used for information storage and processing (the field commonly known as nanoelectronics). We build and operate instruments at the absolute limits given by nature - this challenges creativity, physical insight and technological wizardry. AFMs are a unique tool for the nanoscale: they are capable of imaging, measuring properties and manipulating nano objects such as single electrons, individual molecules or single synapses in almost any environment. As a result, one can discover how atomic scale structure relates to exciting emerging nanoscale properties of matter. In particular, a dynamic, creative and highly collaborative team of students builds or adapts AFM hardware to investigate and manipulate:

• the behaviour of individual electrons in quantum dots (relevant for quantum information processing or catalysis),
• to study how one or a few single molecules conduct electricity and how this depends on the atomic structure of the contacts and interaction with light (relevant for fundamental understanding of charge transport in molecules or to probe the fundamental limits of organic photovoltaics),
• is combining electrochemistry and atomic resolution imaging (relevant to fundamental understanding of the solid-liquid interface or the rate limiting Li ion diffusion in battery cathodes)
• Manipulates and studies individual live neurons (to understand synapse formation or develop a new method to repair life neurons after injury or disease).

Results from these experiments provide experimental data for the stringent testing of modeling. Modeling is very important in understanding the nanoworld, but many approximations commonly made have not been tested experimentally. Experiments that control all degrees of freedom are crucial, as this leaves no room for (educated) guessing, fitting or fudging the interpretation of the data. One has to appreciate that currently modeling and experimental measurement of the conduction of a simple molecule such as C60 only agree to within a factor of 10. This is definitely due to the unknown atomic structure of the contact leads (necessary as input to the simulation) and (probably) due to inadequate modeling. Only if quantitative agreement between modeling and experiment is achieved can one reliably test approximations or claim that one understands nanoscale phenomena.

The Grutter group is driven by exciting fundamental ‘big’ science questions. We are also interested in translating the scientific discoveries to societal relevance including commercial applications. Past team members have gone on to very successful careers in academia, industry or government. For more information please see http://spm.physics.mcgill.ca/

Condensed matter experiment

Figure: Fabrication and imaging of single atom deep pits in a NaCl surface – the individual Cl ions are visible in this ultra high vacuum AFM image (top row). These pits can be filled with molecules – the zoom at the bottom right shows the epitaxial structure of the PTCDA film on NaCl imaged by AFM.
Most striking advances in Condensed Matter Physics are driven by new materials, new applications of these materials, their characterization and their understanding. Dramatic examples include, the discovery of high temperature superconductors and of the discovery of two dimensional electron systems (2DES), with the subsequent finding of the quantum Hall effects in semiconductor heterostructures and more recently in graphene. We believe that combining these different aspects (new materials, new applications, their characterization and their understanding) are the corner stones for significant new discoveries. Hence, our research philosophy is guided by these considerations, which leads to a research that combines all these aspects (synthesis and processing, characterization and modeling).

One of the main foci in our group is life in the quantum world. We are particularly interested in small dimensions and dimensionalities. Why? When reducing, for example, the dimension from 3 to 2 of an electron gas confined in a semiconducting heterostructure, new elementary quasiparticles appear. These particles have an effective fractional charge and obey fractional statistics. They are obtained when a perpendicular magnetic field is applied to the 2D electrons, which leads to the formation of composite Fermions and to the observation of the fractional quantum Hall effect.

By reducing the dimension even further, i.e., to 1D a whole new set of phenomena appear. Because of the inherent electron-electron interactions, the electron gas can no longer be described as a Fermi gas or Fermi liquid but rather as a Luttinger liquid. One of the most fascinating properties of a Luttinger liquid is the separation of charge and spin, i.e., the charge and the spin become independent of each other.

On a more applied level, the miniaturization is of tremendous interest for information technologies. Reducing the dimensions to such an extent that the information is not carried anymore by a macroscopic current but by single electrons, leads to the computing on the nanoscale. An even more fascinating outlook is the possibility to realize a quantum computer. In this case the computational information is the quantum mechanical "state" of an electron.

In particular we work on:

- experimental and theoretical qubit systems based on double quantum dots
- the synthesis and characterization of new materials such as graphene, carbon nanotubes, quantum Hall systems, disordered and exotic superconductors
- transport properties in the quantum limit (close to absolute zero temperatures; theory and experiment)

Our techniques include, transport, ultra-low temperatures (5mK), high frequencies (50GHz), chemical vapor deposition (CVD) synthesis, microfabrication, Raman spectroscopy, scanning probe techniques, and numerical simulations.

Figure: 100 micron sized mono-layer dendritic graphene single crystals (graphlocons), grown on copper using chemical vapor deposition. More information on graphene can be found in our recent review: “Experimental Review of Graphene”, Daniel R. Cooper et al., ISRN Condensed Matter Physics, 501686 (2012).
My research interests are centred on magnetic materials, with particular emphasis on those with frustrated or competing exchange interactions. Typical alloys include a-Fe$_x$Zr$_{100-x}$, a metallic glass which evolves from a weakly frustrated ferromagnet to a spin-glass with increasing iron content, and RFe$_6$Ge$_6$ where a cancellation in the R-Fe exchange leads to a two orders of magnitude difference in the rare-earth and Fe sub-lattice ordering temperatures. My primary research tools are Mössbauer spectroscopy, magnetisation and ac-susceptibility, with magnetic neutron scattering using the neutron scattering facilities at Chalk River and $\mu$SR at TRIUMF in Vancouver playing an increasing role.

Other areas of interest include

- Development of high-performance rare-earth - iron permanent magnet alloys. Current work is focused on the R$_2$Fe$_{17}$ series modified by the addition of carbon and or nitrogen.


- Fine magnetic particles prepared by confined geometry chemistry in various biological and mineral systems.

- Development of gadolinium-based magnetic refrigeration alloys.

- Superparamagnetic spin dynamics in fine particles are being studied using Selective excitation double Mössbauer (SEDM) spectroscopy and $\mu$SR.
The purpose of my lab will be to explore the mechanical properties of light, and to develop new types of sensitive micromechanical devices controlled by photons.

The simplest example of how light can influence the motion of a micromechanical element is radiation pressure, or the recoil a mirrored surface experiences when photons reflect from it. Ordinarily this effect is quite weak, but when photons are trapped by a resonant object such as an optical cavity, a surprisingly weak source of light (a few microwatts, say) can profoundly influence the motion of a micromechanical resonator. The initial goal of my lab will be to exploit similar types of optomechanical coupling to realize micromechanical devices supported primarily by optical forces, thereby replacing traditional mechanical materials with light.

These optically-supported mechanical devices should be quite flexible and find many uses. Their mechanical frequencies and damping parameters will be optically tunable, and they are predicted to achieve an extremely high degree of isolation from the environment. As a result, it should be possible to laser cool these devices from room temperature all the way to their vibrational ground state, and to observe quantum effects in their motion. While this should prove interesting from a fundamental physics standpoint, the realization of coherent quantum motion in micromechanical elements should also enable them to act as an interface to many other types of quantum systems. Additionally, such well-isolated mechanical resonators could find applications detecting sub-zeptonewton ($<10^{-21}$ N/Hz$^{1/2}$) forces or changes in mass on the order of a single proton. Finally, the tunable nature of the optical supports should enable fundamental studies of mechanical dissipation in traditional supporting materials, a subject of central importance to existing technology that is often not well understood.
Is it possible to resolve the elementary atomic motions taking place in molecules during the breaking and making of chemical bonds in the transition state region between reactant and product states? Or to make direct observations of the collective atomic motions leading to structural phase transitions in material systems as they take place? The experimental challenge associated with such measurements has often been referred to as the making of a “molecular movie” and requires that these systems be studied on both their natural length and time scales simultaneously. This can require the ability to obtain atomic level structural information on the timescale of a single vibrational period (~10^{-13} s).

Research in my laboratory is focused on developing technologies that will allow complex transient structures of molecular and material systems to be determined at the atomic level. In particular, this involves engineering new instruments that unite the tools and techniques of electron microscopy with those of time-resolved (ultrafast) laser spectroscopy in novel ways. We are interested in studying photo-induced phase transitions in materials (order-disorder and order-order), where it will be possible to directly determine the changes in atomic configuration that accompany the system’s progress along the physical pathway between phases. These techniques will also be employed to try and understand structural dynamics in functional light-activated nanocomposite, nanostructured and organic materials. An additional area of research will be structural studies of extreme states of matter (i.e. materials under the conditions existing at the core of planets, or plasmas). Extreme conditions can be prepared transiently through interaction with intense laser pulses. Some projects will take place at the Advanced Laser Light Source (ALLS) facility being constructed in Varennes, Quebec, near Montreal - a world class $21M laser facility that will be able to produce femtosecond laser pulses in a range of wavelengths from the mid-IR to X-ray with peak powers greater than 10^{14} W.
The research of my group involves the study of the time evolution in non-equilibrium systems and applications of non-equilibrium statistical mechanics. The main research technique is high resolution x-ray diffraction performed at third generation synchrotrons around the world.

By using high intensity x-ray synchrotron sources we have developed techniques to measure in situ time resolved diffraction with a time resolution of a few milliseconds, both by conventional x-ray diffraction and using the new technique of x-ray intensity fluctuation spectroscopy (often called x-ray photon correlation spectroscopy). We have been using these techniques to study the kinetics of systems out of thermal equilibrium, from first order phase transition kinetics to viscoelastic properties of polymers and rubbers.

We also have projects using x-ray reflectivity to study the structure of metallic thin films and their interfaces. Finally, we are involved in experiments to use the x-ray free electron laser at the Stanford Linear Accelerator Center when it starts up in the next few years.
My research is in the general area of mesoscopic physics. This is a subfield of condensed matter physics concerned with electronic systems which are much larger than the size of an atom, but which nonetheless are strongly influenced by the presence of quantum phase coherence. Examples include nanometer-scale quantum dots formed in semiconductor heterostructures, carbon nanotubes acting as one-dimensional quantum wires, and micron-sized superconducting metallic grains. A central theme in this field is decoherence, the process by which quantum phase information is usually lost as we move from microscopic to macroscopic length scales. Problems in mesoscopics usually involve the complex but interesting interplay between quantum phase coherence, disorder physics, and inter-particle interactions.

I am particularly (but not exclusively) interested in the noise properties of mesoscopic systems. Noise can reveal a wealth of information on the mesoscopic regime not accessible by other means; its study is also directly relevant to attempts at using mesoscopic systems for quantum information processing (i.e. solid-state quantum computation). I am also interested in the emerging area of quantum nano-electromechanics: what happens when one couples a small mechanical resonator to a quantum conductor? Such systems are interesting from the point of view of dissipative quantum mechanics, and because of their potential to be used in ultra-sensitive detectors and in quantum control applications.

Finally, note that though I am a theorist, I try to maintain a close connection to experiment, and have a number of experimental collaborators.

Recent Publications


Awards

Alfred P. Sloan Fellowship - 2007

Figure: Theoretical calculations of the damping of an atomic-force microscopy cantilever by single-electron tunnelling events in a double quantum dot (as a function of two control gate voltages). The bright regions in the middle of the figure correspond to damping arising from coherent quantum tunneling between the two quantum dots, while the remaining features are due to incoherent tunnelling. Experiments testing these predictions are planned in the group of P. Gutter at McGill.
My work deals with the theory of quantum properties of nanometre-scale condensed-matter systems and applications of these systems to quantum and classical information processing. A central motivator for most of my work is the realization that the spin magnetic moment of electrons and holes can be decoupled relatively well from their orbital degrees of freedom, allowing for long-term storage of either classical or quantum information in the spin. A very important fundamental question is then: How long can this information be stored in the presence of influences in a solid-state environment? In the last 5 years, there has been a flood of new experimental and theoretical results suggesting that information can be stored in these systems far longer than previously imagined, but the upper limit is still relatively poorly understood, and is the focus of much of my research. Moreover, there are several interesting theoretical problems related to the transfer of information from spin to charge degrees of freedom, from spin to light (photons), or between collective quantum states of spins and other quantum-mechanical degrees of freedom. To explore these ideas in relatively new nanoscale systems far from equilibrium, it is often necessary to rethink the relevant physical systems “from the ground up, discovering essential features of the underlying physical systems along the way.

To resolve these issues requires an interdisciplinary approach; I try to combine a complete theoretical understanding of the microscopic description of solid-state systems with applications borrowed from more abstract ideas in quantum computing and quantum measurement theory. This combination opens the door to answering a number of intriguing questions, including: How can we control the polarization (or more complex quantum state) of nuclear spins in nanostructures? What materials give rise to the longest spin lifetimes? and What are the roles of electron and nuclear spins in nanoelectronic devices (quantum dots, wires, and wells)? These questions lead to a wide range of potential applications from quantum and classical information to biomedical imaging and precision measurement.

Recent Publications


Most of my work has been in nonequilibrium statistical physics. I am interested in problems at the boundary between condensed matter physics and materials science, such as crystal growth, epitaxy, reaction fronts, spinodal decomposition, and nucleation. By their nature, these problems are multidisciplinary, encompassing physics, chemistry, computational research, applied mathematics, and materials science. With my group, I am investigating universal phenomena in these far from equilibrium systems by nonlinear analysis, and by using the biggest computers we can get our grubby hands on.

My current interests include the growth of a solid binary alloy within a liquid melt near a eutectic point, the behavior of flame fronts growing in a random background of reactants during slow combustion, the morphological instability caused by strain during thin-film growth, texturing patterns during the extrusion of polymer melts, and the nucleation and growth of droplets from a supersaturated solution.

Figure: A series of four snapshots of the simulation of a neutrophil cell following chemical gradients (i.e., smell) to chase and catch another cell. Paper submitted for publication by Sara Najem and Martin Grant, called, “Phase Field Approach to Chemotactic Driving of Neutrophils’ Morphodynamics”. Moving boundary value problem solved with continuous classical field theory.
The research of my group mostly concentrates in two main areas: electronic transport theory in mesoscopic and nanoscopic systems and materials physics of nanotechnology. In nanoelectronics research, our recent work has concentrated on the development of theoretical and computational formalisms as well as their applications to nanoscale electronic device systems including molecular electronics and quantum dot systems. The basic questions we ask are like: how to predict electric current flowing through a molecule connected to the outside world by metallic electrodes or by other molecules? how to find the best operational principles of molecular scale field effect transistors? what physics is behind these principles? how to predict the response of a molecular scale circuit? how to understand strongly interacting electrons in a quantum dot and its implications to transport? etc.. These and many other questions are wide open and challenging. On the technical side, a particularly useful recent development from our group has been the ab initio technique for analysing nano-device characteristics including current-voltage properties, by combining the density functional theory with the Keldysh nonequilibrium Green’s functions. In materials physics, we use both classical and quantum molecular dynamics methods to study problems associated with bulk, surface, and interfaces of solid state systems. Recently we have focused more on materials properties of nanoelectronic devices under external bias and gate potentials. The questions we ask are: how to compute mechanical structure of a nanosystem under external fields and during the flow of current? how to predict current-triggered mechanical phenomena? How to understand correlations of mechanical structural change and electrical transport response? These problems are at the heart of the physics that govern properties of nanometer electro-mechanical systems.
Topological insulators - this new state of matter has been predicted theoretically several years ago (Kane and Mele, 2005) and has only recently been observed experimentally (Hasan group, 2008). A topological insulator is a state in which the bulk of a two or three dimensional material is gapped and does not support any conductivity while the edges are metallic. Moreover, the edge states are helical (their spin is parallel to the momentum direction) and a net spin current may be observed. In two dimensions, due to the confinement of conducting states to the edge their effect can only be seen in Hall conductivity (off-diagonal conductivity). This state is called the spin quantum Hall effect.

Topological superconductors - theoretically predicted materials which not only have topological properties but also superconduct. Moreover, topological superconductors may support ‘Majorana fermions’ in their vortex core. These are elusive particles which are their own antiparticles and have been sought after since 1937. Nowadays, we are closer than ever before to realizing topological superconductors in semiconductor layered structures.

Graphene - though predicted as early as 1948 graphene, a single layer of graphite, has only been achieved experimentally in 2006. Due to its honeycomb lattice structure low energy electrons exhibit conical dispersion \( E = v|k| \). The model for low energy electrons is mathematically equivalent to the description of relativistic massless Fermions in the Dirac model. The physical spin of the Dirac model is played by the sublattice degree of freedom and the helicity is replaced by chirality. This formal similarity between graphene and Dirac Fermions leads to many unique properties. For example, the Klein paradox, the prediction that Dirac Fermions can tunnel through infinitely high barriers may be tested in graphene while high energy experiments are still not feasible.

Unconventional superconductors - I’m interested in the high T\(_C\) cuprates as well as other unconventional superconductors. The common thread to these materials is a pairing mechanism which is driven by interactions. Among these materials are the cobaltates and iron-based two dimensional superconductors.

Recent Publications


Figure: A fourier transform of the local density of states an iron-based superconductor with a magnetic vortex.
My research is at the interface of condensed matter physics and materials science. It uses high-performance computing, principles of statistical mechanics and experiments to understand the fundamental origins of length scale selection in non-equilibrium pattern forming systems found in materials science. These include systems undergoing crystallization from a melt or amorphous phases, particle precipitation, second phase formation, grain growth kinetics and reaction-diffusion processes in heterogeneous materials. Most of these systems serve as paradigms for understanding microstructure evolution during material processing. I am interested in porting over ideas and knowledge from microscopic scales to the scales on which material properties are typically realized in practical applications. This connection of length scales can be achieved by course-graining microscopic theories to yield meso-scale continuum and sharp-interface models. Models thus developed find use in materials engineering applications. Some of the phenomena I study relevance to industrial materials processing, and some of my work is sponsored by industry.

Topics of Research:

- Length scale and morphology selection mechanisms in crystal growth.
- Non-equilibrium selection mechanisms for secondary phases formation in multi-component alloys.
- Grain boundary roughening and anomalous grain growth in polycrystalline network.
- Adaptive mesh refinement techniques for phase field models of microstructure formation.
- Pattern formation of combustion fronts propagating in heterogeneous media.

Recent Publications


Morteza Amoorezaei, Sebastian Gurevich and Nikolas Provatas, Spacing characterization in Al-Cu alloys directionally solidified under transient growth conditions Acta Materialia 58, 6115 (2010).

Figure: Phase field crystal simulation of three-phase coexistence between two solids (red and blue lamellae) and liquid. The contact angle and interface energies are functions of the crystal structures of the solid phases. Atomic positions are shown by the black dots in the left figure.
All of the phenomena of nature are presently understood as being the result of a few species of elementary particles interacting through four forces. In its broadest terms, research in particle physics has as its goals the discovery of the most basic constituents of matter and the forces through which they interact, and the understanding how matter behaves when it is put under very extreme conditions. These goals are linked because our knowledge of the motions of matter in extreme conditions often relies on the limits of what we know about the most elementary particles and forces.

At present, theoretical and experimental research in high energy physics is dominated by the existence of a superbly successful theory, the Standard Model (SM). Because of the dominant role played by the Standard Model, current research divides into two broad parts. The first is concerned with obtaining detailed predictions from the Standard Model, comparing these predictions with measurements and challenging them in extreme kinematic ranges and conditions. The second approach proposes plausible alternatives to the Standard Model to try and improve some of its less attractive features, and with which to contrast the Standard Model when comparing to experimental data. Since these alternative theories predict other, hitherto undiscovered, particles they generally also suggest non-standard phenomena for which one can search.

The McGill High Energy Physics group has vigorous research programs in both experimental and theoretical areas as well as efforts in the related areas of cosmology and astro-particle physics.

Experiment

Elementary particle physics is the investigation of the structure of matter and the forms of its interactions. In the search for the basic constituents at the smallest possible scale, one has to reach with the highest available energies. Experimental particle physics is usually the realm of international efforts in large collaborations of physicists around complex detectors. The McGill high energy groups are actively involved in many of those leading edge ventures. The major experiments our group members are involved in include the ZEUS detector at DESY, the BaBar detector at SLAC, the CDF and D0 detectors at Fermilab, the ATLAS detector at CERN and the International Linear Collider Project.

On November 23rd, 2009, at 14:22 local time, the Large Hadron Collider succeeded in bringing protons beams together at CERN. CERN is the largest international particle physics research centre, located in Geneva, Switzerland. Here is a display of the the first collision event candidate in the ATLAS detector.

Prof. Brigitte Vachon in front of the ATLAS detector under construction at CERN. The ATLAS detector is an integral part of the Large Hadron Collider which will look for the evidence of new physics beyond the Standard Model by colliding protons on protons at the unprecedented energy of sqrt(s)=14 TeV. The photo was taken in January 2007.
**Theory**

Our research interests are diverse, covering most of the active topics in high-energy theoretical physics. Some of the topics on which we have worked over the past few years include:

- **Elementary-Particle Physics**
  - Neutrinos
  - Precision Electroweak Physics
  - Strong Interactions
- **Field Theory**
  - Black Holes
  - Duality
  - String Theory
  - Supersymmetry
- **Theoretical Cosmology**
  - Inflationary Cosmology
  - Theory of Cosmological Perturbations
  - Superstring Cosmology
  - Baryogenesis
- **Interdisciplinary**
  - Particle Astrophysics
  - Condensed-Matter Physics

The racetrack inflation model (Cline 2004) was one of the first rigorous constructions using the extra dimensions of string theory to drive inflation. This is the potential energy diagram as a function of the real (X) and imaginary (Y) parts of the Kahler modulus. Inflation occurs in the flat region, and the field rolls to one of the two minima. The model predicted a spectral index of 0.96 for the power of the CMB fluctuations before the recent WMAP measurement in agreement with that prediction.
As an experimental physicist, I am especially interested in high energy collisions to get new insights into the nature and structure of matter.

A McGill group is involved in the international ZEUS collaboration. Most of our work is related to the physics of electron-proton collisions. These take place at the HERA accelerator of the DESY research center in Hamburg, Germany. ZEUS and HERA actually ran until July 2007. With the realms of data collected, the physics analyses should be completed in the following two or three years.

A large number of research topics are accessible with ZEUS. My main current interests lie in the domain of deep inelastic scattering of punctual electrons on protons, thus probing the content of the proton very close to the attometer ($10^{-18}$m!) scale. This enables us to determine the structure function of the proton, which is basically a description of its parton (quark and gluon) content. Strange particle production has also been studied successfully by our group, its overall aim being to probe the sea quark content of the proton and to understand the actual mechanisms of the fragmentation processes. Another current project is the observation of jets of particles: not only do jets testify of the quark and gluon content of the proton, but they also represent a powerful tool to test the Quantum Chromodynamics (QCD) theory of the strong interaction and to determine the value of its as coupling constant. The available kinematic range in ZEUS is even sufficiently large that the constant’s running properties can even be observed within this measurement.

Photoproduction on proton, by which a quasi-real photon is exchanged, yields on the other hand a large amount of very relevant information on the many-sided and puzzling nature of the photon. Some of the observables are its vector meson behaviour, its direct interaction signals or evidences of its partonic structure. Via the observation of jets, I am interested in details of the hard processes, which should provide essential informations on the photon parton densities.

In the footsteps of LEP, both the Large Hadron Collider (LHC) and the ATLAS detector at CERN are being built to investigate further symmetry breaking and the origin of mass by searching for the Higgs particle. Canadian groups were very active building part of the detector and are now preparing for the data taking starting in the Summer of 2008. The ATLAS/McGill group, of which I am a member, is contributing to the trigger and energy measurement optimizations.

The next generation of accelerators can no longer be circular because of large synchrotron energy losses and their power demands. The planned International Linear Collider will ideally complement the LHC and investigate the properties of the Higgs with high precision. Part of the contributing Canadian groups (McGill and Regina) joined the CALICE collaboration to work on innovative calorimetry, R&D projects and challenging developments of energy flow algorithms. I am committed to these exciting endeavours for the future.
Since 1999 the BaBar experiment, located at the PEP-II asymmetric “B-factory” at the Stanford Linear Accelerator Center (SLAC) in California, has recorded the decays of over 130 million pairs of B-mesons and their antimatter counterparts (“B-bar” mesons). These exotic particles contain a heavy b-quark and their decays can provide insight into many poorly-understood aspects of particle physics. In my research, I utilize this enormous data sample to search for rare B-meson decays into states containing charged or neutral leptons, such as electrons and neutrinos. The rates of these decay processes are predicted to be enhanced in theoretical models describing physics beyond the “Standard Model” of particle interactions, due to contributions from previously-unobserved exotic particles. Observation of one of these rare decay processes occurring at a rate which is significantly in excess of the Standard Model expectation would therefore provide the first evidence of non-Standard Model physics.
What is as heavy as a gold atom, yet point-like and indivisible? The most massive known fundamental particle of nature: the top quark.

The main goal of my research is to study the unique properties of top quarks in order to understand physics at the smallest distance scale which ultimately dictates what today’s universe looks like. Specifically, I am interested in understanding why elementary particles have the mass they are observed to have; a fundamental question which has far reaching consequences in describing the universe as we know it. Part of my research involves precisely measuring known properties of the top quark to look for small deviations from theoretical predictions. I am also interested in searching for new particles, like the Higgs boson, which could predominantly interact with the heavy top quarks.

My research involves the study of the highest energy particle collisions ever produced in a laboratory. Currently, there is only one place in the world where top quarks can be directly produced: the Tevatron collider at the Fermi National Accelerator Laboratory (Fermilab) near Chicago. I study the results of these proton-antiproton collisions using the DZero experiment.

I am also involved in the next generation of particle physics experiments, which will open up a completely new window of high energy physics. The large Hadron Collider (LHC), under construction at the CERN Laboratory in Switzerland, will collide protons at an unprecedented energy; seven times higher than the energy available at the Tevatron. The results of these collisions will be studied using the ATLAS experiment. Currently, I am involved in the design and commissioning of the ATLAS experiment’s trigger; a complex system built to identify, in real-time, potentially interesting collisions out of the millions per second. Operation of the Large Hadron Collider and the ATLAS experiment at CERN will begin in 2008.
My research engages high-energy matter-antimatter and matter-matter particle colliders and multipurpose detector technologies to seek an improved understanding of the basic constituents of our universe and the forces that govern their interactions. Many of my research interests have involved the bottom (b, or beauty) quark, a unique fundamental particle with an electric charge of -1/3 and a mass about five times that of a proton, to further our understanding of Nature through its strong and electroweak interactions. We study b quarks by examining how they are created from energy, how they combine with other quarks to form hadrons, and how they change flavour to become lighter (charm or up) quarks. Recently, I've been using b quarks as a means to study much heavier particles like the highly sought-after Higgs boson.

I am involved in the Collider Detector at Fermilab (CDF), ATLAS, and SuperB experiments. My current interests include studying Standard Model Higgs decays to bottom quarks, detecting quark, gluon, and photon jets to hunt for new phenomena like quark substructure, and seeking out new physics by studying rare processes in extremely large collision-data samples. It is an exciting time in experimental particle physics! Enquiries about graduate study opportunities are welcome.

Recent Publications


Evidence for a Particle Produced in Association with Weak Bosons and Decaying to a Bottom-Antibottom Quark Pair in Higgs Boson Searches at the Tevatron, T. Aaltonen et al. (CDF and DZero Collaborations), Physical Review Letters 109, 071804 (2012)

Observation of a New Particle in the Search for the Standard Model Higgs Boson with the ATLAS Detector at the LHC, G. Aad et al. (ATLAS Collaboration), Physics Letters B 716, 1 (2012)

Dr. Adrian Buzatu explains his McGill PhD thesis research, leading to first evidence of Higgs particles coupling to beauty (bottom) quarks, to Professor Peter Higgs in St. Andrews, Scotland (August 2012). [Photo: Huong Nguyen]
Professor Brandenberger’s research interests span a wide range of topics in theoretical cosmology. A first research area is inflationary universe cosmology. The inflationary universe scenario has provided a theory of the origin of the small density fluctuations which can be measured in cosmic microwave background temperature anisotropy maps and galaxy redshift surveys. The original predictions for observables have been spectacularly confirmed in recent experiments. Current research in this area focuses on looking for imprints of Planck-scale physics in observables, and on more detailed studies of inflationary reheating.

The theory of cosmological perturbations has become the cornerstone of modern cosmology since it provides the bridge which connects the physics of the very early universe (which is determined by Planck-scale physics) with observations. In the past, Professor Brandenberger has made key contributions to the development of this subject, in particular providing an extension of the analysis to higher-dimensional space-times. Current research at McGill in this area focuses on the study of the back-reaction of cosmological perturbations on the background space-time. Initial calculations indicate that this back-reaction might lead to a dynamical relaxation of a large initial bare cosmological constant, leaving behind a remnant cosmological constant which automatically plays the role of dark energy.

Professor Brandenberger has made pioneering contributions to the emerging field of superstring cosmology. All of our current models for the early universe (inflationary cosmology included) break down at very high densities, i.e. in the very early universe. Input from new fundamental physics is required if one is to understand questions such as the presence/absence of an initial cosmological singularity, or the reason why there are precisely three large spatial dimensions. Superstring theory is the best available framework to tackle these questions. Professor Brandenberger has started a new research effort to use recently developed tools in string theory such as the AdS/CFT correspondence and the web of string dualities to obtain an improved understanding of the early universe. One model to have emerged from this work is the string gas cosmology scenario, a scenario in which string matter (including string momentum and winding modes) is coupled to a classical background. This model has the potential to explain why there are only three large spatial dimensions and why the other spatial dimensions are dynamically confined to a microscopic size. Recently, the McGill-Harvard group has shown that string gas cosmology leads to a scenario for the origin of structure in the universe which can provide an alternative to cosmological inflation and makes specific predictions for upcoming observations. One of the concrete goals of the ongoing research is to put the string gas cosmology scenario on a firmer string theoretic basis.

In collaboration with members of the Astrophysics Group, Professor Brandenberger has initiated a broad search for signatures of cosmic strings in new observational windows such as CMB polarization maps, 21cm redshift surveys and high redshift galaxy observations. Since cosmic strings are predicted in a broad class of particle physics models beyond the "Standard Model", searching for cosmological signatures of strings leads to a way of probing particle physics beyond the Standard Model which is complementary to accelerator searches such as those done at the LHC.

Recent Publications


R. J. Danos, R. H. Brandenberger and G. Holder, A Signature of Cosmic Strings Wakes in the CMB Polarization, Phys. Rev. D
I am currently focusing on the quest for theoretical explanations of dark matter, which comprises 85% of the mass density of the universe, but whose identity remains a mystery. There are several experimental hints that dark matter might be manifesting itself nongravitationally: in excess 511 keV and 130 GeV gamma rays from the galactic center, and unexplained events in underground detectors searching for dark matter colliding with nuclei. It is also possible that the Large Hadron Collider (LHC) will produce dark matter directly, or see indirect effects of its interactions with other particles. The decays of the recently discovered Higgs boson into photons can be changed as a result of such interactions. Dark matter can also be entwined with the mechanism for producing the normal (baryonic) matter of the universe. I am investigating models where scalar dark matter enhances the strength of the electroweak phase transition and enables electroweak baryogenesis.

Figure: Feynman diagrams for a model of 130 GeV scalar dark matter annihilating into photons at the galactic center, as suggested by recent Fermi Large Area Telescope data; see [http://arxiv.org/pdf/1205.2688.pdf](http://arxiv.org/pdf/1205.2688.pdf)
My research has been concentrated on various aspects of string theory, quantum field theory, mathematical physics and string cosmologies.

In string cosmologies, my interests have been mostly on embedding inflationary models in string theory. I am also interested in studying standard cosmological solutions, evolution of the universe etc. directly from M/string-theory.

In quantum field theory and string theory, I have studied various aspects of brane constructions for gauge theories, gauge-gravity dualities for more realistic theories, M-theory, F-theory and flux compactifications. My recent interests have been on moduli stabilisations in string theories in the presence of fluxes.

In mathematics and mathematical-physics, my interests have been on manifolds that are not Calabi-Yau, i.e non-Kahler manifolds. These manifolds may or may not even be complex. I have been studying these manifolds and their mathematical properties as solutions to string theory.
My research is in the area of theoretical particle physics and string theory, with an emphasis on problems in quantum gravity. Most recently I have focused on two sets of problems, involving black holes and cosmology, which have the potential to shed light on fundamental questions involving the quantum structure of space-time.

Black hole physics provides an ideal theoretical laboratory for the study of quantum gravity, since quantum effects necessarily become important near the singularity at the center of a black hole. Over the past several years I have used various techniques to study quantum black holes in string theory, most recently by understanding higher order corrections to Einstein’s equations that arise in the quantum effective action of string theory. This leads to some surprising insights into the geometry and thermodynamics of these mysterious objects.

A second set of questions, motivated by cosmology, involves the description of time-dependent universes in string theory. Perhaps the most interesting questions involve inflating universes, such as de Sitter space, which although apparently simple have proven notoriously difficult to understand in string theory. I am interested in constructing de Sitter backgrounds of string theory, and in holographic descriptions of these inflating cosmologies. I have also studied various simple time-dependent universes which, although they share many features with realistic cosmological models, can be solved exactly. Remarkably, many of these backgrounds are described by completely unitary quantum theories, even though they apparently contain big bang and big crunch singularities.

Recent Publications


Holographic Mutual Information is Monogamous, P. Hayden, M. Headrick and A. Maloney, arXiv:1107.2940 [hep-th]
Besides the familiar electromagnetic interactions, the Standard Model of Particle Physics says that there are two other interactions, the strong and weak interactions, which are quite similar to electromagnetism. The strong interactions are like electromagnetism but with 8 electromagnetic fields, which furthermore participate in interactions with each other. Mostly because of this self-interaction, the physics the strong interactions (Quantum Chromodynamics or QCD) is much more complicated than the theory of electromagnetism. Although we have very strong experimental evidence that it is correct, we do not always know how to uncover its predictions.

My work deals with the strong and weak interactions in many-body contexts, in which their physics is particularly rich (and our understanding is particularly incomplete). How much like electromagnetism, and how differently, does QCD behave? One recent problem I have studied is understanding QCD plasma instabilities. In electromagnetism, ordinary plasmas of charged particles display fascinating phenomena when the distribution of charge carriers is out of equilibrium and anisotropic. Such a plasma is unstable to spontaneous growth of magnetic fields and bunching up of the charge carriers into current filaments. This instability dominates the physics of nonequilibrium plasmas. I have been working to understand the behavior of the strong interactions under analogous circumstances, an anisotropic momentum distribution of quarks, the constituents of the protons and neutrons. We expect that such anisotropic plasmas should be produced during heavy ion collisions, such as those studied in the RHIC experiment at Brookhaven Labs in the United States.

We have shown that plasma instabilities, with the spontaneous development of the strong-electromagnetic fields, should be a generic feature of nonequilibrium strong-interaction plasmas. However, the evolution of the magnetic field is very different than in electromagnetism, in ways we do not completely understand yet. I am investigating both the physics of these large color-magnetic fields, and their potential implications in heavy ion experiments.

Among the tools we use to study plasma instabilities, lattice gauge theory is one I am also interested in in its own right. This technique allows rigorous investigation of some aspects of QCD even at strong coupling. I am also interested in developing techniques to use the lattice for several problems in field theory, in particular for studying supersymmetric theories and supersymmetry breaking, as well as improved methods of studying renormalization using the lattice as a tool.
My recent research activity has been at the String Theory interface between Theoretical High-Energy Physics and Mathematics, mostly Algebraic Geometry. More generally, I am interested in String Theory as a candidate framework for the next unification step in theoretical physics, as well as for addressing fundamental questions about quantum space-time.

The branch of mathematical physics stemming from string theory is the youngest and one of the most promising: Efforts of high-energy physicists trying to understand quantum gravity, and to unify the fundamental interactions, have required the use of sophisticated mathematical machinery and, conversely, contributed new results in pure mathematics. The characteristic feature is that the interaction has been with areas of mathematics, that, for most of the 20th century, have been disconnected from developments in theoretical physics, in particular algebraic geometry and low-dimensional topology.

The basic connection between geometry and string theory arises because of the geometrization of gravity in Einstein’s General Theory of Relativity, and because string theory is a theory of quantum gravity. Thus, string theory requires (or provides, depending on the point of view) a notion of quantum geometry. Although one is presumably just scratching the surface of this idea, the fact that that can generate non-trivial statements about ordinary geometry is in itself highly remarkable.

The projects which I have worked on recently have to do with mirror symmetry and the topological string with D-branes. The topological string can be viewed both as a toy model for ordinary (super)string theory, and as a truncation of the (compactified) superstring to the (for phenomenological applications most relevant) vacuum sector. Mirror symmetry is one basic duality that relates different string backgrounds, and provides a powerful tool to manipulate physical and mathematical data associated with Calabi-Yau manifolds. D-branes (boundary conditions for open strings) are fundamental players in explaining string dualities. The intersection of these three topics provides a rich source of fresh problems to work on. There are also connections with various other recent developments in mathematical string theory, which I am also exploring.
In addition to teaching, service, and clinical work, members of the Medical Physics Unit (MPU) are involved in basic and applied research. The research is generally done under the auspices of major clinical departments at McGill, such as Oncology, Radiology, or Neurology-Neurosurgery, and is supported by McGill teaching hospitals, hospital foundations, outside agencies, such as CIHR, NSERC, FQRNT, FRQ, NIH or industry which through grants supports special interest medical physics projects developed by MPU staff.

Most of the research by MPU members is of an applied nature, generally done in collaboration with McGill medical staff, and related to patient care through improvements in diagnostic and therapeutic procedures involving radiation. The research collaboration between members of the MPU and McGill medical staff is excellent and results in important advances in the field of medical physics, radiology, oncology and neurosurgery. Graduate students working on their M.Sc. or Ph.D. thesis projects form an important component in the research effort of the MPU members. Students are encouraged to present their research findings at national and international medical physics meetings and often the research presented in their theses is summarized in the form of articles in the scientific literature.

Both the imaging division and the clinical division of the MPU have an excellent reputation worldwide for innovative and interesting research projects. The imaging division is well known for the development of new computerized image processing techniques based on CT, DSA, MRI, and PET images. Members of the division developed software systems for 3-D vascular reconstruction and for stereotactic intracranial target localization. They also developed a 3-D treatment planning software program for stereotactic radiosurgery, new techniques for cerebral blood flow measurements, and new detectors for use with PET scanners.

The clinical division is known for the development of new radiotherapy techniques, such as total body irradiation with a sweeping photon beam in the treatment of leukemia, rotational electron beam therapy in the treatment of mycosis fungoides, electron arc therapy with the angle-beta concept in the treatment of large superficial lesions, and stereotactic dynamic radiosurgery in the treatment of vascular, metastatic and primary intracranial lesions. Members of the division have developed a fast and user friendly software package for treatment planning in brachytherapy and stereotactic radiosurgery.

The group is also working on increasing the basic understanding of radiation dosimeters for clinical radiation therapy. New dosimeters and dosimetry techniques are optimized and protocol procedures and data are calculated using Monte Carlo techniques and measurements. Research in this area translates into clinical applicability by recommendations put forward by task groups (through European, Canadian and American medical physics organizations). In addition, Monte Carlo transport simulation procedures are used to calculate dose distributions in patients to evaluate the accuracy of clinically used radiotherapy treatment planning systems. This research also involves dose calculations in deforming patient structures imaged with 4D-computed tomography. Finally, the clinical implementation of a novel radiation treatment delivery device, the few-leaf electron collimator, that allows for the clinical use of energy modulated electron radiation therapy (EMET) is being investigated. This technique has the potential to be of significant advantage for certain head and neck cancers as well as breast cancers.

People

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Nonlinear and Atmospheric Physics

The Weather and Climate as Physics Problems

Since the 1980’s, the nonlinear physics and atmospheric physics group has worked on a series of new geophysical paradigms. A particularly exciting one is the idea that atmospheric dynamics repeat scale after scale from large to small scales in a cascade-like way. The key is recognizing that as the scales get smaller, the horizontal gets “squashed” much more than the vertical so that the stratification which starts out being extreme (structures very flat at planetary scales) become rounder and rounder at small scales. This allows the scaling (and the stratified cascades) to occur over huge ranges of scale. The cascade mechanism implies that the variability builds up scale by scale; the resulting “intermittency” is huge and is a consequence of the large range of scales. It has nonclassical statistical features, the result is a multifractal process. The physical implications are that atmospheric fluxes of energy, moisture etc. are far from uniform, they are concentrated in storms, and even in the centre of storms.

The classical laws of turbulence (Kolmogorov, Bolgiano, Obukhov, Corrsin...) are based on strong assumptions of isotropy and homogeneity of the fluxes and fields, they are expected to be high level laws “emergent” from the lower level laws of continuum mechanics and thermodynamics. When the nonlinearity (Reynolds number) is strong enough one obtains “fully developed turbulence”. However, due to the atmosphere’s strong stratification and heterogeneity, it was believed that they would only apply over very narrow ranges of scale (several hundred meters at most). The developments of anisotropic scale invariance and multifractals effectively generalize them allowing them to hold up to planetary scales.

In the last five years, with the help of massive amounts of in situ, aircraft, satellite data, and reanalysis data, these emergent laws have been extensively verified up to planetary scales. An overall in depth review (for atmospheric scientists) has recently been published: “The weather and climate: emergent laws and multifractal cascades” [Lovejoy and Schertzer 2013; a powerpoint presentation is available here. It was also found that over almost all of their ranges, numerical models of the atmosphere (and reanalyses) also have cascade structures, so that cascades do indeed provide stochastic models of deterministic Global Circulation Models (GCM’s) and can be used to understand and improve the latter (for example by “stochastic” subgrid parameterisations).

When these scaling ideas are applied to the temporal structure of the atmosphere, they predict that there is a fundamental change in behavior at about ten days; this is the lifetime of planetary sized structures; it is determined by the solar (turbulent) forcing of about one milliwatt per kilogram. Indeed, all the atmospheric fields show qualitative changes in their statistics at about 10 days. It turns out that whereas fluctuations grow with scale in the weather regime, over scales longer than this, the fluctuations tend to cancel out - the signs of the fluctuation exponents change from positive to negative. Averaging over longer and longer periods thus gives smaller and smaller fluctuations, apparently converging to a well-defined “climate”. However, this turns out to be an illusion: at scales of 10-30 years (industrial period, 50-100 years, preindustrial), the exponents again change sign, with fluctuations again increasing with scale. The intermediate “macroweather” regime is dominated by weather dynamics, the longer regime is the true climate; it is the focus of much of our research in the last few years (see e.g. chapters 10, 11 of Lovejoy and Schertzer 2013, but also Lovejoy and Schertzer 2012. Scaling techniques

Representative temperature series from weather, macroweather and climate (bottom to top respectively). Each sample is 720 points long and was normalized by its standard deviation (bottom to top: 0.35°C, 4.48°C, 2.59°C, 1.39°C, dashed lines indicate means). The resolutions are 0.066 s, 1 hour, 20 days and 1 century, the data are from, Montreal Canada (the roof of the physics building at McGill), Lander Wyoming, the 20th Century reanalysis and Vostok (Deuterium paleotemperatures, Antarctic) adapted from [Lovejoy, 2013].
(including the much neglected Haar fluctuations) are transforming our view of the climate by allowing us to compare scale by scale instrumental, paleo (proxy) data and outputs of numerical models.

**Solid Earth Geophysics**

In the area of solid earth studies, we have shown that the surface topography is a universal multifractal, showing that - contrary to prevailing wisdom - scaling surfaces cannot generally be regarded as self-affine fractals (Gagnon et al 2006). Similarly, the variability of the earth’s surface magnetic field can be explained by a similar scaling stratification of the rock susceptibility (Lovejoy et al 2001). Interestingly, the lithospheric stratification is opposite to that of the atmosphere becoming stronger at smaller rather than larger scales. Analogous results apply to the rock density and geogravity fields (Lovejoy et al 2008), see Lovejoy and Schertzer 2007 for a review.

**Other applications**

Other applications include the analysis and simulation of scaling properties of ocean and ice surfaces, chemical pollution, low frequency human speech, hadron jets and the large scale structure of the universe. As disparate as some of these applications may seem, they are linked by the common theme of (nonlinear, dynamical) scale invariance, a symmetry principle whose generality and significance is great.

**Nonlinear Geophysics**

This work is part of a family of approaches to geophysics collectively termed “nonlinear geophysics”. For more information on this and on its place in the American Geophysical Union and the European Geosciences Union, see “Nonlinear geophysics: why we need it”.

This shows the typical (Haar) fluctuations for the Lander data (upper left), and paleo Antarctic data (from the EPICA core, near and similar to the Vostok core). Also shown is the globally averaged (at 2° resolution) fluctuations from the Twentieth century reanalysis. The various regimes are shown, along with power law (straight) reference lines with the slopes as indicated.
In ordinary fluid flows one typically exploits macroscopic continuum and thermodynamic laws that emerge from the chaos of huge numbers of interacting particles. Similarly, higher-level laws emerge in sufficiently nonlinear fully developed turbulence. They are based on scale symmetries in which small, medium and large scale structures are related by highly intermittent cascades with many novel features. My research has been aimed at extending these emergent laws so as to apply them to geosystems, especially in discovering new emergent laws of the weather and climate. These open new doors for the understanding and modelling of the atmosphere over vast ranges of space and time scales. One of the keys is the recognition that while planetary scales are extremely stratified, as we move to smaller and smaller scales, the horizontal is more and more squashed so that structures become rounder and rounder - yet the dynamics remain scale invariant. Similarly, up to about ten days, fluctuations increase with time scale, beyond that spatial interactions become less and less effective and fluctuations begin to decrease in amplitude: this is the emergence of a new regime. However, at scales longer than about 30 years, fluctuations again increase: this is the climate. The development and testing of these laws was possible by exploiting a golden age of geophysical data and with the help of new paradigms and models of nonlinear dynamics especially fractals and multifractals. Work in my group has thus included the analysis of thousands of satellite images, state of the art lidar data, aircraft data, the stereophotography of rain, meteorological and climate models, the exploitation of massive meteorological data bases. The work includes new paradigms for the transfer of radiation through multifractal clouds, and for stochastic forecasting. Other applications include solid earth geophysics: for example, the earth’s surface also has a scale symmetry and the variability of the earth’s surface magnetic field can be explained by a scaling stratification of the rock susceptibility. These and other apparently disparate applications are linked by the common theme of (nonlinear, dynamical) scale invariance, a symmetry principle of great generality.
Nuclear Physics

Nuclear physics began with the discovery of radioactivity, transmutation of matter, and the discovery of the nucleus. The latter two discoveries were made by Sir Ernest Rutherford. McGill University’s long and strong tradition of excellence in nuclear physics began with Rutherford’s tenure at McGill between 1898 and 1907 during which he discovered the transmutation of matter. The same tradition of excellence continues on to this day.

Today, nuclear physics encompasses a wide range of modern physics. The traditional study of nuclei and their reactions is still a vibrant part of modern nuclear physics. In the latter part of the 20th century, however, a new and exciting field of nuclear physics started to emerge, the study of nuclear matter under extreme conditions.

Nuclear Theory at McGill (Gale, Jeon)

Soon after the advent of Quantum Chromodynamics (QCD), the theory of the strong nuclear force, physicists began to realize that at extreme temperatures of trillions of Kelvin, the protons and neutrons in nuclei should, in effect, melt, and the released quarks and gluons should form a completely new phase of matter. The hunt for this new state of matter, dubbed the Quark-Gluon Plasma (QGP), soon began and the powerful relativistic heavy ion colliders at the Brookhaven National Laboratory and at CERN have now confirmed that under this extreme and highly relativistic condition, QGP is indeed the phase of the nuclear matter. Yet, many properties of the produced QGP, such as the lowest viscosity ever measured, were completely unexpected.

To put QGP in perspective, this kind of temperature (about a billion times hotter than the surface of the sun) existed in nature only when the Universe was about a micro-second old, about 1 cubic millimeter of QGP contains enough energy that it could power current Canadian economy for few hundred million years, yet it flows more freely than the superfluid helium!

The study of QGP is the new frontier of modern nuclear physics. The Nuclear Theory Group at McGill has long been playing a central role in the development of this exciting new field. The group currently consists of two professors (Charles Gale and Sangyong Jeon) and more than a dozen students and postdoctoral fellows. The group also has strong ties to researchers in the high energy theory group at McGill and collaborators in the US, Europe and Asia. The main focus of our study is QGP and the relativistic heavy ion collisions in which it is made. The research topics vary widely from purely theoretical to numerical simulations. What ties all of our efforts together is the question, How does one use heavy ion collision phenomenology to learn about QGP? This calls for a comprehensive model of the full evolution of heavy ion collisions.

To achieve the extreme conditions necessary to produce QGP, heavy nuclei such as gold or lead are
accelerated to almost the speed of light and made to collide with each other. The produced QGP then cools as it expands and eventually turns back into ordinary matter. To accurately describe and predict the behavior of these processes requires understanding of the initial nuclei, energy and entropy release during the collision, formation of QGP, expansion and cooling, and finally the phase transition back to ordinary nuclear matter. While all these are happening, high energy quarks (called the jets) may traverse QGP shedding some of its energy, and photons from black-body radiation are being produced at each stage.

To understand all of the above is a challenging task to say the least. Yet, the goal of the our group is nothing short of building a comprehensive model of the full heavy ion collision and QGP evolution encompassing the essence of all of the above!

To achieve this goal, some of us are working on applying string theory techniques to the study of QGP, some of us are studying quantum field theories at extremely high temperatures, some are building the most advanced hydrodynamic models of the QGP evolution, and some are studying the effect of QGP on ultrarelativistic particles that are traversing it. Yet, there are many important un-answered questions such as What is the nature of the initial conditions? How does the QGP form so quickly? that are waiting for bright minds.

To add excitement, the LHC has started to produce a copious amount of new heavy ion collision data which contains more surprises that await theoretical resolution. Our group is fully engaged in studying all aspects of these issues. This is an exciting time to be a nuclear physicist, especially at McGill!

**Nuclear Experiment at McGill (Buchinger)**

The formation of the elements that make up our universe, from the remnants of the big bang that created it, continues to be a fascinating mystery. It is thought that at least part of the production of the heavier elements took place during explosive astrophysical events (supernovae, x-ray bursts etc.) that are powered by nuclear reactions among short-lived, radioactive nuclides at the limits of nuclear binding.

The atomic masses of these nuclei are essential to understanding these processes because they determine the energy released and determine the path of the nuclear reaction chains that take place in these events. Furthermore, the atomic masses of nuclei that participate in super-allowed beta-decay provide a unique opportunity for tests of fundamental symmetries in the standard model for particle physics.

Nuclear mass measurements are done using the Canadian Penning Trap Mass Spectrometer (CPT) at the Argonne national Laboratory that collects short life nuclei produced in reactions at the ATLAS heavy-ion accelerator. With this system, nuclear masses of isotopes with lifetimes as short as 30 milliseconds are measured with very high accuracy and sensitivity. Nuclear mass measurements are also performed using the TITAN facility at TRIUMF in Vancouver where the unstable nuclei are produced by a different process; nuclear spallation.

In recent years, techniques originally used for atomic spectroscopy have been applied to measure such nuclear properties as spin, electric and magnetic moments, and the change of charge-radius between neighboring isotopes. These techniques are based on the precise measurement of atomic hyperfine structure in the interaction of laser beams with atomic beams obtained from isotope separators. The laboratory has pioneered in the development of a number of high sensitivity techniques for such studies.

Our group participates in a program of such measurements at the ISAC radioactive beam facility at TRIUMF. Using a spectroscopic method known as collinear fast beam laser spectroscopy and by making use of existing facilities such as the TITAN ion trapping system and material science beta-NMR and beta-NQR it is possible to perform spectroscopy measurements on ion beams with intensities as low as a few tens of ions per second. The on-line work at TRIUMF is supported by in-house activities at McGill where components of the apparatus are developed and tested before being integrated into the on-line set up.
My primary interest is heavy ion collision theory in the intermediate energy range. In this energy range the important questions to ask are:

• Can we extract information about the nuclear equation of state?

• Do we see a liquid-gas phase transition in the lower beam energy experiments?

• What is the proper theoretical framework which can be used to describe intermediate energy heavy ion collisions?

Much progress in these areas has been made and McGill has been a solid contributor. I am also interested in studies of symmetry energy in nuclear physics at densities away from normal nuclear density.
My current research mostly deals with the theoretical study of matter under extreme conditions of temperature and density. This general area straddles nuclear and particle physics, but also involves aspects of condensed matter and astrophysics. Put another way, we are trying to explore and understand the phase diagram of QCD, the theory of the strong interaction. These studies eventually lead to a better understanding of the nuclear equation of state and this is relevant for the physics of the early Universe, the theoretical modeling of neutron stars, and for the understanding of nuclear collision dynamics.
My current research interest lies primarily in contemporary nuclear theory as applied to relativistic heavy ion collisions. I can identify my field of research as the intersection between phenomenology and formal theory. In current high-energy nuclear physics, we have many interesting phenomena uncovered at facilities such as SPS and RHIC. We also have an accurate theory of strong interaction, Quantum Chromodynamics (QCD), which in principle should be able to describe and explain all nuclear phenomena. However, there is a long distance between formal perturbative QCD and the observed phenomena. My research goal is to continue to fill in that gap using techniques of non-equilibrium quantum field theory and numerical simulations of many-body QCD. The long term objective of my research is a comprehensive theoretical understanding of current and future heavy ion collision phenomenology. In order to obtain this goal, I employ classical and quantum chromodynamics for the initial stages and effective field theory of hadrons and their constituent quarks in the later stages. Eventually, these theoretical consideration will become a foundation for a comprehensive simulation model.
Our research is focused on the investigation of fundamental nuclear properties, and specifically masses and radii. The work involves laser spectroscopy experiments for the determination of isotope shifts and hyperfine structures over long isotopic chains, as well as nuclear mass measurements using Penning traps. We are collaborating in the Canadian Penning Trap experiment at Argonne National Laboratory, the TITAN Penning Trap experiment at TRIUMF and the Collinear Laser Spectroscopy Experiment at TRIUMF. The experiments determine moments, radii and masses of nuclei far from stability and provide data for nuclei of relevance in stellar processes and for the refinement of nuclear models in general. In addition, high precision mass measurements provide an important ingredient for testing the standard model using results from low energy experiments. The latter point is also exploited through an alpha-neutrino angular correlation experiment at Argonne National Laboratory. In house, at McGill, we are developing experimental methods for efficiently measuring the low abundant exotic nuclei in the online experiments at TRIUMF and Argonne. Current work concentrates on the development of a collinear laser spectroscopy set-up using pulsed ion beams.

For more information see also the following links:

http://www.triumf.ca/laser-spectroscopy


http://inspirebeta.net/search?p=find+buchinger&
action=Search

Recent Publications


Our spectroscopy group at McGill studies fundamental nuclear properties: nuclear masses, radii, spins and moments. Very accurate mass measurements are essential for testing symmetries in nuclear and particle physics and for understanding the various processes of element building in astrophysics. These studies are carried out at the Canadian Penning Trap facility located at the Argonne National Laboratory. Beams from Argonne’s ATLAS accelerator bombard targets to produce proton-rich nuclei of importance in the rapid-proton capture astrophysical rp-process. An intense $^{252}$Cf fission source also produces neutron-rich isotopes: mass measurements on these nuclides are needed for the understanding of the astrophysical r-process in which elements are produced in type II supernova explosions. Ions produced by these sources are cooled and guided into the Penning trap. Here the ions orbit in the high magnetic field of a superconducting magnet; measurement of the orbital cyclotron frequency then gives a precise measurement of the mass. For long-lived isotopes, mass measurements of the order of parts per billion have been made.

We are currently also collaborating in the construction of the TITAN ion trap at the TRIUMF facility in Vancouver. To make measurements of high precision on isotopes with very short lifetimes it is necessary to boost the ions to very high charge states prior to injection into the measurement trap. TITAN does this by bombarding the ions with the intense beam of an EBIT (Electron-Beam Ion Trap). With charge states of the order of $q=20$, it will be possible to make measurements better than 1 part in $10^{8}$ on isotopes with half-lives as short as 20 milliseconds. TITAN is the first of this new generation of EBIT-coupled mass spectrometers. It is now in its final construction stages and should make its initial mass measurements in 2007.

To measure nuclear radii and nuclear shapes, we borrow techniques from atomic physics. In an atomic spectrum, a transition line splits into a number of components (the hyperfine structure), whose wavelengths depend on the size, shape, and spin of the nucleus. Many of the really interesting phenomena (sudden changes of nuclear shape, for example) occur in exotic nuclei lying far from nuclear stability. At TRIUMF we make these measurements by collinear laser spectroscopy, overlapping the fast ion beam with a co-propagating laser beam. Here TITAN will also play an important role. In the TITAN cooling stages, sets of ion traps bunch the ions to produce pulses. Overlapping the beam pulses with the laser, and gating the detection system to collect data only during the beam overlap permits measurements on ion beams with very low intensity. The improved signal:noise ratio of this system and the high isotope production yield at TRIUMF will permit measurements on hitherto unavailable chains of exotic isotopes.
Particle Astrophysics

Particle Astrophysics (Hanna, Ragan)

Particle Astrophysics (also called Astroparticle Physics) is a relatively new area of research where ideas and data from elementary particle physics are applied to topics in astrophysics and cosmology, or vice versa.

On the theoretical side this has been going on for many years where, for example, theories of nuclear and particle physics can be used in calculating details of stellar evolution or the very early history of the Universe itself.

Experimentally, one can use techniques and instruments developed for use at accelerator laboratories to make astronomical observations using gamma rays, neutrinos and cosmic rays, thus extending our view of the Universe beyond that accessible using more the more traditional messengers of astronomy, such as optical photons and radio waves. For example, in searches for exotic particles such as those which may make up the mysterious dark matter, astrophysical observations are complementary to lab-based searches and can explore a greater range of masses.

The current (September 2012) map of known very high-energy (VHE, $E>100$ GeV) sources, from [tevcat.uchicago.edu](http://tevcat.uchicago.edu), in galactic coordinates. The different colours represent different types of source, including active galactic nuclei (red), supernova remnants (green), and unidentified sources (grey). The total VHE source count has increased by an order of magnitude over the last decade, with VERITAS discovering nearly 20 of those since 2007.

The McGill efforts in Experimental Particle Astrophysics are currently concentrated in the field of Very-High-Energy (VHE) gamma-ray astronomy using the VERITAS detector array.

The four 12-m telescopes of the VERITAS array, now operating at the Mt. Hopkins site (Arizona) to detect high-energy gamma rays.
My research roots are in experimental high energy physics and I am applying the techniques I know from that field to projects in high energy astrophysics. Specifically, I am a member of the VERITAS collaboration, which operates an array of four 12-m telescopes on Mount Hopkins in southern Arizona. This array is used to detect very high energy astrophysical gamma rays, in the energy range from 100 GeV to 10 TeV, by measuring the Cherenkov radiation emitted by the particles in the air showers they produce when impacting the upper atmosphere.

Very high energy gamma-ray astronomy is the science of extreme astrophysics. The sources of TeV gamma rays are non-thermal and often transient; examples include pulsar wind nebulae, active galactic nuclei and colliding stellar winds. It is also possible that some of the gamma-rays are produced by annihilation of dark matter particles in the centres of dwarf galaxies and we are searching for the signal of such a phenomenon.

I also maintain an interest in instrumentation and have a few hardware projects in detector development. Currently, I am involved in development of a gamma-ray imager for safety and security applications and also have a project to adapt the VERITAS telescopes for detecting fast optical transients.

Recent Publications


Detection of Pulsed Gamma Rays Above 100 GeV from the Crab Pulsar, E. Aliu et al., Science 334, 69, (2011)

A connection between star formation activity and cosmic rays in the starburst galaxy M82, V.A. Acciari et al., Nature 462, 770-772 (2009)


A new mirror alignment system for the VERITAS telescopes, A. McCann, D. Hanna, J. Kildea, M. McCutcheon, Astroparticle Physics 32, 325-329 (2009)


Figure: Evidence of very-high-energy gamma rays from the Crab Pulsar. The gamma-ray flux is plotted vs the pulsar phase as determined from radio observations. Lower energy data from the Fermi Large Area Telescope is shown below for comparison.
My primary research interests are presently in the area of particle astrophysics, where astrophysical phenomena are studied through particle physics techniques and used to understand the high-energy physics of the cosmos.

My main research effort is the VERITAS project based at Mount Hopkins, Arizona. This is a ground-based gamma-ray detector whose primary goal is to observe astrophysical sources of high-energy gamma rays in the energy range between about 50 GeV and 10 TeV. A number of different classes of objects are known to be strong emitters in this energy regime, including active galactic nuclei (black-hole driven galaxies), supernova remnants, pulsar-wind nebulae, and microquasars; this energy regime is thought to be crucial to a thorough understanding of these sources.

VERITAS detects the Cherenkov light produced when energetic particles impinge on the upper atmosphere. It uses an array of four 12-m telescopes to image the gamma-ray showers; the multiple-telescope aspect improves the resolution of the instrument and gives it exquisite sensitivity in the 100 GeV to few-TeV regime.

In addition to the VERITAS experiment, I have an interest in other topics in astroparticle physics and more traditional (accelerator-based) particle physics, as well as in new detector and instrumentation technologies. For VERITAS and for a previous experiment called STACEE, I helped design and implements specialized parts of the electronic triggering systems.