Proposed PHYS 590 Research Thesis Topics, 2026

Gunnar Blohm (Gunnar.Blohm@queensu.ca)

The Blohm lab uses a combination of computational models and experimentation to understand sensory-motor processes in the brain - we do neuro-physics (http://www.compneurosci.com/). Proposed projects require knowledge in numerical methods.

1. Design, implement and analyze an artificial neural network that performs multi-sensory integration in a causal fashion. Multi-sensory integration is combining redundant information (e.g. you can localize a dog by hearing it bark and by seeing it; and both). However you don't want to combine unrelated information (e.g. seeing a dog and hearing a meow).
2. Design and implement spiking neural network models to investigate distributed computational principles, such as synchronization in oscillatory sub-nets, entrainment of oscillations, stochastic facilitation, and their consequence for macroscopically measurable electro-magnetic signals, such as measured with Electroencephalography (EEG) or MEG.
3. Design and implement an analysis pipeline for directed functional brain connectivity based on magnetoencephalography (MEG) recordings using methods such as partial directed coherence. Then devise a novel visualization method to analyze task-related changes in functional connectivity.
4. Neuro-robotic performance: design and implement EEG analytics / decoding for brain-driven online robotic control and generative visuals/music with the ultimate goal of developing a performance arts show. This project will be in collaboration with Ingenuity Labs and the School of Drama.
5. We are open to suggestions from students with specific other interests: feel free to contact me!

Joseph Bramante (joseph.bramante@queensu.ca)

1. **Superradiant quantum detection with coherent atomic transitions**
   CATCHY (Coherent Atomic Transitions from Counter-pulsed Hydrogen) is a quantum sensing experiment that exploits superradiant emission from coherently prepared atoms to achieve detection sensitivity scaling as N^2, where N is the number of emitters. In conventional detectors, each atom acts as an independent sensor and sensitivity grows only as N, so that reaching new physics requires scaling up detector mass for a linear gain in sensitivity. In a coherently prepared medium, transition amplitudes from indistinguishable emitters

add before squaring, meaning a gram-scale target with $\sim 10^{22}$ coherent sites can in principle compete with tonnes of classical material. CATCHY realises this by exciting cold parahydrogen (pH_2) into its first vibrational state using counter-propagating nanosecond laser pulses. Because the ground and excited states share the same parity, single-photon E1 dipole transitions are forbidden and the excited state is metastable, but two-photon E1$\times$E1 de-excitation is allowed and proceeds superradiantly over macroscopic volumes when the atoms are pumped into phase.

Projects in CATCHY span laser and cryogenic engineering, atomic and optical physics, and quantum sensing theory. On the hardware side, there are opportunities in designing and characterising the pulsed laser system (counter-propagating gigawatt-class nanosecond pulses at ~ 0.26 eV), developing the cold parahydrogen target cell and its cryogenic environment, and building the photon detection system that must resolve signal from background with nanosecond timing. On the atomic physics side, key questions involve maximising the coherence fraction of the pH_2 sample, understanding and extending the decoherence time beyond the current $\sim$10 ns benchmark, and numerically simulating the coupled Maxwell-Bloch field equations that govern the nonlinear amplification dynamics. On the theory side, there are projects in mapping the sensitivity of coherent atomic de-excitation to a broad class of weakly coupled fields beyond dark photons, connecting the N^2 superradiant scaling to the wider quantum metrology framework of Heisenberg-limited detection, and exploring alternative atomic and molecular targets that may offer longer coherence times or access to different mass ranges.

2. **Heavy dark matter rocks**

   Ancient minerals offer a uniquely powerful approach to detecting dark matter too heavy for conventional underground experiments. Because the flux of dark matter through a detector decreases with increasing particle mass, meter-scale experiments become insensitive for dark matter heavier than 10^{18} GeV; but a billion-year-old mineral has accumulated the equivalent of a gigaton-year exposure. Projects in this area span geological fieldwork, laboratory microscopy, and astrophysical modeling. On the geology side, there are opportunities in sourcing and characterizing candidate minerals from pegmatites, establishing thermal histories through isotopic geochronology and fission track counting, and validating that samples have retained damage tracks over geological time without annealing. On the readout side, techniques including X-ray fluorescence mapping, chemical etching with optical and atomic force microscopy, and potentially other scanning methods must be calibrated against known damage features to establish detection thresholds for micron-scale tracks. Finally, robust sensitivity projections require astrophysical modeling of the local dark matter velocity distribution and density averaged over the sample's integration time, including the effects of Milky Way mass assembly, satellite mergers such as the Large Magellanic Cloud, and dark matter substructure.

Tucker Carrington (Tucker.Carrington@queensu.ca)

All projects in my group involve using numerical methods to study properties of molecules. All 590 projects are designed to be doable but of interest to experienced researchers.

Possible topics include:

1. A new interpolation-type method for numerically solving the Schroedinger equation. It takes advantage of the near symmetry of the Hamiltonian matrix.
2. A new method for numerically solving a multi-dimensional Schroedinger equation using non-orthogonal basis functions

Mark Chen (mchen@queensu.ca)

1. **The SNO+ Neutrino Experiment**

   The SNO+ experiment studies fundamental neutrino properties using a 780 tonne liquid scintillator target. In particular, we plan to study low energy solar neutrinos; make a precision measurement of neutrino oscillation parameters by detecting anti-neutrinos produced by nuclear reactors; study the composition of the Earth's crust and mantle by measuring the geo-neutrinos; probe the development of a supernova explosion and study neutrino behaviour in high density matter by detecting the neutrinos from a supernova (should one occur while we are running!); and attempt to determine whether or not neutrinos are their own anti-particles and determine the absolute neutrino mass by searching for neutrinoless double beta decay.

   SNO+ has taken data in our "pure scintillator" phase. PHYS 590 students have the opportunity to be involved in the analysis of this data, with possible topics including detector simulations, event classification, event reconstruction, and analysis of calibration data.

2. **LiquidO detector development**

   LiquidO is a new particle detection technique that aims to exploit an "opaque" scintillator to localize the light produced by particle interactions in the medium. This allows the pattern of energy deposition to be "imaged" by collecting and reading out the light using an array of wavelength-shifting optical fibres coupled to SiPM detectors. Possible projects for students include: building and testing a prototype mini LiquidO detector; testing novel formulations of liquid scintillator; simulating and studying different classes of events, including employing machine-learning techniques to classify various signals using their different event patterns.

Philippe Di Stefano (philippe.distefano@gmail.com)

1. **Potassium-loaded scintillators:** student will investigate how to load scintillators with as much potassium as possible, looking out for light yield, as well as for chemical and aging effects
2. **A setup to measure thermal contraction at cryogenic temperatures:** After a literature review, the student will design a setup based around an existing 10 K cryostat to measure thermal contraction of materials, including polymers, from room temperature down to 10 K. Methods may include laser triangulation and image metrology.
3. **Simulations to optimize the design of the KDK+ experiment using Geant4:** KDK+ seeks the elusive b+ decay of 40K, and will use a liquid scintillator loaded with 40K, and surrounded by an efficient gamma tagger.
4. Build a model to determine CdA in cycling based on power and speed. Compare to data.
5. Trigger rate calculation for vacuum surface alphas in the DEAP 3600 dark matter search.

Laura Fissel (laura.fissel@queensu.ca)

1. **Study interstellar or galactic magnetic fields with the TolTEC polarimeter**

   This project would be an opportunity for a student to study magnetic fields by analyzing early data from the new TolTEC camera on the Large Millimeter Telescope in Mexico. Depending on the interests of the student this project could include studying polarized synchrotron of quasars to determine how their emission varies over time, or using TolTEC polarized dust emission to map out magnetic fields at exquisite detail in nearby clouds of star-forming interstellar gas.
2. **Study the formation of new stars in a magnetized molecular cloud.**

   Protostars are formed from dense knots of gas and dust that collapse under gravity, forming a disk which accretes material on to a dense object (the protostar). In this project you would study the magnetic fields, molecular gas, and light from young stars to study dense cores that are forming multiple protostars in a high mass star forming region. Your goal will be to understand the physical state of these cores: Are they being compressed by an ionization front? Are they collapsing under gravity? Are they supported by the magnetic field? This project will require working with data from the Atacama Large Millimeter Array (polarization and spectral line cubes), some basic statistics and computer programming, and may require learning to use some data reduction and manipulation software such as CASA.

3. **The Balloon-borne Very Long Baseline Interferometry Experiment**
   Balloon-borne telescopes operate in the stratosphere (about 3-4x as high as a commercial jet plane would fly) where they can observe colors of light that would otherwise be absorbed by the Earth's atmosphere. Our team is currently preparing the Balloon-borne Very Long Baseline Interferometry Experiment (BVEX) for a second flight from Brazil in the summer of 2027, which we hope will demonstrate that balloon-borne radio telescopes can augment and improve global Very Long Baseline Interferometry telescopes, which are responsible for the very highest resolution images in astronomy. There are projects to help us take and analyze BVEX data, build and test calibration equipment for BVEX, or to help us design our next-generation version of BVEX: mm-BVEX.

Guillaume Giroux (gg42@queensu.ca)

1. **The search for dark matter with the PICO bubble chamber**
   PICO is an international collaboration working at searching for dark matter at SNOLAB using superheated liquid detectors, or bubble chambers. The most recent iteration of the experiment, PICO-40L, is now taking data and will allow the exploration of new dark matter models. PICO-500 is the next-generation, ton-scale bubble chamber, to be constructed at SNOLAB. Research topics are available in the fields of data analysis (dark matter search data and calibration data), detector simulation, detector design and R&D.
2. **The search for dark matter with the NEWS-G spherical proportional counters**
   NEWS-G is an international collaboration aiming at the detection of low-mass dark matter particles using spherical proportional counters (SPCs) installed in the deep underground laboratories of LSM in France, and SNOLAB in Canada. A 140-cm SPC made from ultrapure copper is now installed at SNOLAB and will have unprecedented sensitivity to low-mass dark matter particles. Research topics include data analysis, detector simulation, and detector calibration using SPCs located at Queen's.

Michela Lai (michela.lai@queensu.ca)

Multiple astrophysical and cosmological observations suggest that the Universe is mostly made of dark matter: a form of matter—potentially a particle—that cannot be detected with any telescope or antenna. Nevertheless, as the Solar System orbits the centre of our galaxy within its dark halo, we are constantly exposed to a subtle "wind" of dark matter. Noble-liquid experiments, particularly those using argon and xenon, currently focus on the search for Weakly Interacting Massive Particles (WIMPs), dark matter candidates heavier than a few hydrogen atoms. However, WIMPs are not the only candidates accessible to these detectors, nor is dark matter the only physics they can probe. My research focuses on expanding the physics reach of current and future dark matter experiments, through both data analysis and R&D in our newly established laboratory. Possible student projects include:

1. **Sensitivity projections for a tonne-scale dark matter experiment using xenon-doped argon.** This project trains the student in a cutting-edge technology gaining international momentum. It involves fundamental noble-liquid physics, Monte Carlo simulations, and an understanding of the global context of dark matter searches.
2. **Development of an online remote-monitoring system for a cryogenic setup.** This project focuses on communication between hardware and software within the research lab, with an emphasis on the MIDAS framework developed at TRIUMF.
3. **Characterization of noises in Silicon Photomultipliers.** This project trains the student in fundamental measurements of noises in semiconductor-based photosensors, both at room temperature and at cryogenic temperatures. It includes hands-on experimental work and signal processing data analysis, as well as Monte Carlo simulations.

Ryan Martin (Contact: ryan.martin@queensu.ca)

Our group (the GeRMLab) has a number of research interests, and we can work with motivated students to develop a project that is aligned with our research, the student's interests, and the skills that the student wishes to develop. Our research is in the field of experimental particle astrophysics with a focus on neutrinoless double-beta decay and dark matter searches. We participate in the NEWS-G experiment to search for dark matter and the SNO+ and LEGEND experiment to search for neutrinoless double-beta decay. Our focus is on developing machine-learning based techniques to analyze data from these experiments as well as extending their applications to other fields.

1. **Denoising autoencoders** We use deep neural networks in an autoencoder configuration to remove electronic noise from time-series data as well as for anomaly detection. We can propose projects to improve the technology and/or to expand it to other applications, for example in astrophysics. The specific project would be developed based on the student's interests.
2. **Machine-learning based position fitter for SNO+** We have developed machine-learning based methods to infer the position of events in the SNO+ detector based on the pattern of photomultiplier hits. We can propose a variety of project around improving and characterizing different machine-learning based position fitters.
3. **Physics education** We are generally interested in physics education research. Past projects have included using machine learning to predict grades and

identify students in need, quantifying the effects of imposterism in physics students, and developing laboratory instruction that is focused on skill development.

4. **Large Ge detector characterization** Our lab hosts a very large high-purity germanium particle detector prototype for next generation searches in neutrinoless double-beta decay. We are interested in characterizing how well one can infer the position of energy depositions based on the signals that are recorded from the device. This project would involve a component of modelling detector signals as well as data collection to then test the model.

Jean-Michel Nunzi (nunzijm@queensu.ca)

We study light matter interaction in optoelectronic devices. One current topic is the self-induction of diffractive patterns based on so-called stimulated Wood anomaly that can be used in two practical domains on interest:

1. Diffractive structures for the passive cooling of buildings and structures.
2. Real time optical processing of images using a reservoir computing paradigm.

Anna Panchenko (anna.panchenko@queensu.ca)

Computational Biophysics lab, https://panchenko-lab.org/

1. **Project 1: Molecular Dynamics Simulations of Biomolecules**

   This project will focus on studying the dynamics of chromatin. The student will use molecular modeling and molecular dynamics simulations to investigate how histone modifications or disease mutations influence the chromatin stability. The work may involve analyzing conformational dynamics and identifying collective motions that regulate chromatin function. The project will provide training in computational physics methods applied to complex biological systems and will involve close collaboration with experimental groups studying chromatin structure and regulation. The project will contribute to the development of integrative approaches that combine simulations with experimental measurements.

2. **Project 2: Machine Learning for Interpreting Biomolecular Simulations**

   This project will develop deep-learning approaches to analyze large datasets generated by molecular simulations of chromatin-associated proteins. The student will design algorithms to detect structural patterns, dynamical states, and residue signaling pathways in high-dimensional simulation data. Methods may include dimensionality reduction, clustering, and neural network models that connect molecular conformations with functional outcomes.

Nahee Park (nahee.park@queensu.ca)

1. **Cosmic Ray Propagation studies with HELIX and future magnet spectrometers**

   Cosmic rays are high-energy charged particles arriving at Earth from sources throughout our Galaxy and beyond. A better understanding of particle propagation through our Galaxy is the key to understanding new features of the cosmic ray flux (such as an unexpected excess of anti-matter) recently discovered by space-based experiments. HELIX, a long-duration balloon-borne experiment that will fly 40 km above sea level for several days, aims to provide detailed measurements of cosmic-ray isotopes needed to explain these puzzling observations. To achieve its scientific goals, HELIX requires precise measurements of particle trajectories and velocities. The HELIX instrument comprises a 1 Tesla superconducting magnet, a gas drift chamber, a time-of-flight system, and a ring Cherenkov counter. HELIX had a successful first flight in 2024 summer from Kiruna, Sweden, and is preparing for a second flight from Antarctica in the near future. The potential projects range widely from detector hardware testing and detector support system development to Monte Carlo simulation and software development for data analysis. Here are examples for this year's potential projects: designing and measuring the efficiency of Winston cones for the ring-imaging Cherenkov counter, estimating the probability of particle inelastic interactions at 35 km altitude, developing an AI-based event finder, aligning the system for the silicon strip sensor, and designing Sr-90 electron collimator and scanner for scintillating fibre metrology.

2. **Detector developments for future neutrino telescopes**

   The IceCube neutrino telescope, a cubic-kilometre-sized detector array located under the South Pole, has opened a new window on the Universe by discovering a high-energy astrophysical neutrino flux above a few TeV. The origin of these neutrinos is still unclear. Studying the properties of this neutrino flux requires building larger detectors than IceCube with better optical sensors. Given the limited resources to fill a detection volume larger than a cubic kilometre, a cost-efficient and innovative detector design is necessary. Here are examples of this year's potential projects: correlated and uncorrelated event rate studies for multiple-photomultiplier modules for IceCube Upgrade and P-ONE, exploring detector sensitivity to low-energy neutrino interactions, studies of the environmental dependence of background rate changes, and muon reconstruction for an underwater neutrino detector.

Nir Rotenberg (nir.rotenberg@queensu.ca)

1. **Active chiral quantum photonics**

   The advent of chiral quantum photonics, where on-chip interactions between photons and individual quantum emitters are directional, has enabled the design of efficient quantum logical gates and networks and a variety of non-reciprocal photonic devices that operate at single-photon energies. This thesis project will, for the first time, theoretically model the way in which such chiral interactions can be actively controlled using quantum optical nonlinearities. Our goal is to understand the fundamental physics at this intersection of chiral and nonlinear quantum optics, and to exploit these effects to all-optically control the phase of quantum photonic states.

2. **Cryogenic solid-state quantum optics**

   The new quantum nanophotonic lab at Queen's is being constructed to access and study new frontiers of quantum light-matter interactions at the nanoscale. More specifically, we are interested in the nonlinearities that result when individual photons interact with single quantum emitters (in our case, quantum dots which act as meta-atoms), and how additional photons can alter these interactions on ultrafast time scales. This thesis involves the design and construction of a cryogenic microscopy setup capable to efficiently interfacing single photons with single-emitters. This highly hands-on project will involve the construction of optical setups and coding of software to interface with state-of-the-art cryogenic and quantum electronics equipment.

Nir Rotenberg and Bhavin Shastri (nir.rotenberg@queensu.ca / bhavin.shastri@queensu.ca)

1. **Neural photonic control of solid-state emitters**

   Solid-state quantum emitters such as the semiconductor quantum dots that we study have emerged as leading candidates for the creation of quantum photonic states (single and entangled photons). These emitters are naturally embedded in semiconductor membranes, which is both the strength (enabling precise control of their photonic environment) and weakness (coupling the quantum state to an inherently noisy environment) of this platform. This thesis will explore the way in which a photonic neural network (enabled by silicon photonics) could provide active control of the state of a single quantum dot, focusing on the long-term stabilization and rapid manipulation of the state. Both the emitter response and photonic neural network will be modelled, leading to a design of the network parameters and determination of its operational limits and fidelities.

Bhavin Shastri (bhavin.shastri@queensu.ca)

1. **Photonics for Artificial Intelligence, Neuromorphic Computing, and Quantum Machine Learning**

   A central theme of our research is studying photonic physics for photonic computing, neuromorphic photonics, and quantum neuromorphic photonics by unifying nanophotonics (study of light at small scales) and complex systems (e.g., neural networks) on emerging substrates (e.g., compound semiconductors on silicon). Our interdisciplinary research focuses on the design and experimental demonstration of integrated photonic devices and systems for applications to neuromorphic computing, artificial intelligence (AI), and quantum machine learning.

Please contact Prof. Shastri to discuss potential topics before signing up. Students are expected to propose their own topics based on their interests, recent papers (listed below), and the Shastri Lab website.

1) J. Ewaniuk, J. Carolan, B. J. Shastri and N. Rotenberg, "Realistic quantum photonic neural networks," arXiv:2208.06571 [quant-ph]

2) B. J. Shastri, A. N. Tait, et al. "Photonics for artificial intelligence and neuromorphic computing," Nature Photonics 15, 102–114 (2021).

Kristine Spekkens (kristine.spekkens@queensu.ca)

1. **Probing Galaxy Evolution with Star-Forming Gas**
   How do galaxies like the Milky Way evolve? Where and how do they get their gas? How is their dark matter distributed? What is the fate of the smallest galaxies in the universe? All of these outstanding astrophysical questions can be probed using observations of the star-forming gas in nearby galaxies. This PHYS590 project will focus on one aspect within this broad theme, with the specific project tailored to the student's interest. Example projects include constraining the atomic gas content in the smallest and faintest known galaxies, searching new survey data for the ionised gas shreds of colliding galaxies, or writing code to derive the orbital velocities of the gas in Milky Way-like systems to measure dark matter.

Greg van Anders (gva@queensu.ca)

1. Current priority areas in our group concern the interplay between physics-based or physics-inspired methodologies and machine learning and its applications. This includes physics-based methods for training neural networks (e.g., Babayan et al., Nature Communications 2026 - a previous Phys 590 project) as well as physics-based reasoning for estimation and classification problems in physics and beyond. Work in our group on these topics is evolving quickly; I encourage interested students to contact me for more information on specific projects that are currently underway.

Larry Widrow (widrow@queensu.ca)

1. **Galactic Dynamics with Gaia**

   Gaia, a space telescope operated by the European Space Agency, is measuring positions and velocities for 1 billion stars in the Milky Way or about 1% of the total number of stars. Gaia's phase space maps provide an unprecedented opportunity to probe the dynamics of our galaxy and test models for interactions between the stellar disk and the dark matter halo. Possible projects will use simulations, theoretical astrophysics, and statistical modelling to explore this data set and various problems in galactic dynamics. The project is suitable for a student with a strong interest in computational and mathematical physics. Course work in astrophysics, while useful, is not essential.

Alex Wright (awright@queensu.ca)

1. **The SNO+ Neutrino Experiment**

   The SNO+ experiment studies fundamental neutrino properties using a 780 tonne liquid scintillator target. In particular, we are studying low energy solar neutrinos; making a precision measurement of neutrino oscillation parameters by detecting anti-neutrinos produced by nuclear reactors; studying the composition of the Earth's crust and mantle by measuring the geo-neutrinos; probing the development of a supernova explosion and study neutrino behaviour in high density matter by detecting the neutrinos from a supernova (should one occur while we are running!); and attempting to determine whether or not neutrinos are their own anti-particles and determine the absolute neutrino mass by searching for neutrinoless double beta decay.

   PHYS 590 students have the opportunity to be involved in the analysis of this data, with possible topics including detector simulations, event classification, event reconstruction, and analysis of calibration data.

2. **The Scintillating Bubble Chamber Experiment**

   The Scintillating Bubble Chamber (SBC) experiment is a new liquid argon based bubble chamber experiment. Liquid argon is a scintillating medium, and the combination of scintillation light in a bubble detector allows SBC to operate with extremely low thresholds and provides interesting possibilities for background discrimination. This will allow SBC to carry out a competitive search for low mass dark matter particles and potentially study neutrino properties through a coherent neutrino scattering measurement near a nuclear power reactor.

   Potential PHYS 590 projects include studies molecular dynamics simulation studies to better understand the interaction between bubble nucleation and scintillation light production in liquid argon, threshold studies using the data from the SBC-Fermilab detector, and background studies for SBC-SNOA+LAB.