Nuclear Physics
Quantum Information Science Awards Abstracts

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Nuclear Physics Pre-Pilot Program in Quantum Computing
Martin J. Savage, University of Washington (Principal Investigator); Joseph Carlson, Los Alamos National Laboratory (Co-Investigator); William Detmold, Massachusetts Institute of Technology (Co-Investigator); Thomas Papenbrock, University of Tennessee (Co-Investigator)

Quantum Simulation for Nuclear Physics – Theory

Proposal for the ANL Physics Division to begin the development of a quantum information science program in the context of Nuclear Physics

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Quantum computing, and quantum information science more broadly, is potentially on the brink of having a transformational impact on science – and nuclear physics in particular – because there are Nobel prize level problems that simply cannot be addressed with existing classical computing methods. However, a direct realistic implementation of quantum chromodynamics (QCD) on a quantum computer is still at least a decade away. It is therefore critical that simpler frameworks that represent approximations to QCD begin to be studied using quantum computers, so that the nuclear physics community can begin to build the expertise and knowledge needed to study QCD on a quantum computer. This proposal aims to address this need by making first steps toward simulating a quark-level quantum field theory on a quantum computer. We will use the Nambu-Jona-Lasinio (NJL) model, which is a chiral effective theory of QCD that encapsulates dynamical chiral symmetry breaking. The NJL model therefore generates dressed quark masses even in the chiral limit, and represents an excellent framework from which to study the properties of the pion on a quantum computer. In addition, once a realization of the NJL model is implemented on a quantum computer numerous phenomena can be explored, *e.g.*, it may be possible to make the first steps in the study of the phase transition from baryon to quark matter, where these quantum computer calculations can then be verified using existing implementations of the NJL model at finite temperature and density. We will implement these calculations on the 43 qubit quantum simulator managed Argonne's Leadership Computing Facility, and once the codes are working we can then test them on real quantum hardware (e.g. IBM's superconducting qubit quantum computer).

This proposal describes the theory component of a program to develop a leading quantum information science program at Argonne National Laboratory. The experiment component of this program has submitted a proposal to build a quantum simulation apparatus based on neutral atoms trapped in an optical lattice. This proposal would also provide theory support to this experimental endeavor.

Investigating Natural Radioactivity in Superconducting Qubits

Joseph A. Formaggio, MIT (Lead)
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Tremendous strides have been made over the last few decades in developing superconducting ``artificial atoms''. These electronic circuits include lithographically defined Josephson tunnel junctions, inductors, capacitors, etc. When such circuits are cooled below their transition temperature, these superconducting system behave as quantum mechanical oscillators (also called superconducting qubits). Superconducting qubits are leading candidates for quantum information applications.

A crucial metric for the performance and ultimate viability of quantum processing is the ability to achieve long coherence times over which quantum computations can be carried out. Over the past decade, the quantum coherence of superconducting qubits has increased more than five orders of magnitude, due primarily to improvements in their design, fabrication, and, importantly, their constituent materials and interfaces. However, the coherence times observed are expected to be longer. Despite this progress, the observed coherence times appear to fall far short of theoretical predictions. Excess quasiparticles are observed to limit coherence times in superconducting qubits.

We propose to investigate whether natural radiation and cosmogenic activity might be the source of the quasiparticle excess, and determine if the levels of radioactivity inherent to the laboratory and materials are consistent with the observed excess. If confirmed, the research could pave the way toward longer coherence times, effectively strengthening the technology for quantum processing.

Suppression of the Internal Conversion Decay of Th-229m

PI: Stephan Friedrich, Lawrence Livermore National Laboratory

^{229m}Th is the only known isomer whose nuclear transition to the ^{229}Th ground state has an energy in the range of tunable lasers. That makes ^{229m}Th very interesting for quantum information applications and for nuclear clocks that are based on laser excitation of this transition. Unfortunately, despite 40 years of effort, the transition energy of 7.8 eV is only known to an accuracy of ±0.5 eV. This uncertainty is too large to justify a laser search for the exact transition energy.

We propose to use our unique superconducting tunnel junction (STJ) radiation detectors with an energy resolution of ~1 to ~2 eV FWHM to measure the energy of ^{229m}Thwith an accuracy below 0.05 eV. ^{229m}Th will be generated by the alpha decay of a ^{233}U source that is thin enough for the ^{229m}Th daughters to escape. Earlier experiments to implant ^{229m}Th directly into the STJ detector and look for its decay were unsuccessful, because ^{229m}Th in solids decays by internal conversion with a life time of only 7 µs and the 7.8 eV signal is obscured by the preceding impact of the ^{229m}Th recoil ion. We therefore now propose to place a wide-band-gap MgF_2 crystal between the ^{233}U and the STJ detector to capture the ^{229m}Th daughters. We will examine whether the ~10 eV band of MgF_2 suppresses the ^{229m}Th decay by internal conversion and allows the transmission of the decay gamma into the STJ detector.

If successful, this would allow the use of superconducting detectors to directly measure the decay energy of ^{229m}Th with an accuracy needed to start a laser search for the exact transition energy. This will be an important step towards using ^{229}Th as a qubit for quantum information and developing a nuclear clock with an accuracy of 1 part in 10^{19} based on this transition.

Superconducting Quantum Detectors for Nuclear Physics and QIS

Valentine Novosad, Physics Division and Materials Science Division, Argonne National Laboratory (PI)

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Argonne National Laboratory proposes to develop superconducting nanowire detectors for a wide range of nuclear physics experiments and with many more applications outside of nuclear physics including QIS, nanophotonics, and numerous applications requiring high-efficiency single-photon detectors. Superconducting nanowires have characteristics which open up new experimental opportunities or greatly enhance the figure of merit when utilized in existing experiments. These characteristics include superior timing and position resolution, radiation hardness, low dark count rate, high detection efficiency, and the capability to operate in strong magnetic fields.

The outlined research project takes a two-stage approach, where at first, the effort is focused on the design and microfabrication of prototype devices for detecting photons in the visible/UV range. These devices will be tested and their performance characterized. Most importantly, the researchers will measure and optimize the detector performance in strong magnetic fields. This test is a critical first step towards the proposed flagship experiment, the photodisintegration of polarized deuterium. For this experiment, the superconducting nanowire detectors will be integrated with an existing polarized target system, thus creating an active polarized target. This new target system leverages the unique capabilities of the superconducting devices to identify recoiling protons through secondary ionization photons. This flagship experiment will dramatically highlight the technology's tremendous potential for widespread adoption in nuclear physics. Although its development is only proposed within the first stage of this research project, the active polarized target system is expected to have a high impact by opening up a new class of experiments in nuclear physics.

In the project's second stage, the devices will be designed in single and multi-layered detector configurations, and tuned to detect charge particles. These devices will initially be tested with radioactive sources, demonstrating the detection of α decay. In the latter stages a range telescope prototype will be constructed to measure the penetration depth of low energy light ions with a few hundred nm precision. The range telescope device will be tested using a detector development beam line at Argonne's ATLAS facility. Additionally, an extreme forward ion detector for the Electron Ion Collider will be explored for development in the project's third year.

In parallel with the proposed R&D, we plan to explore commercialization opportunities and transform the developed detector technology into a successful commercial product for large-scale nuclear physics experiments, and potentially for quantum sensing, and secure communication.

Nuclear Physics Pre-Pilot Program in Quantum Computing

Martin J. Savage, University of Washington (Principal Investigator)
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Some of the Grand Challenge problems facing Nuclear Physics require classical computing resources that exceed what can be delivered during the exascale era. At the heart of these challenges are finite fermion density systems exhibiting exponentially large classical resource requirements to describe their quantum states or to sufficiently reduce sampling uncertainties in observables plagued by a sign problem. Systems afflicted with such classical computational requirements span diverse energy and length scales, from quantum chromodynamics to nuclei to astrophysical environments. Technologies and techniques in Quantum Computing (QC) and Quantum Information Science (QIS) may allow these Grand Challenge problems to be addressed without exponentially large computational resources. We are establishing a consortium of scientists to further identify and address problems in nuclear physics that may be amendable to solution using QC and QIS, and estimating the resource requirements to achieve such solutions. This consortium is engaging with experts in QC and QIS, including those at technology companies, through consortium-wide meetings to facilitate the sharing of ideas and algorithms, and is beginning to coordinate the theoretical nuclear physics community, including its workforce development strategy.