Snowmass2021 - Letter of Interest

Quantum Computing Applications to Reactor Antineutrino Experiments

Thematic Areas:

■ (CompF6) Computational Frontier: Quantum Computing
■ (NF06) Neutrino Frontier: Artificial Neutrino Sources

Contact Information:
Submitter Name/Institution: Andrea Delgado (Oak Ridge National Laboratory)
Contact Email: delgadoa@ornl.gov

Authors: Andrea Delgado (Oak Ridge National Laboratory)
Alfredo Galindo-Uribarri (Oak Ridge National Laboratory, University of Tennessee - Knoxville)
Blaine Heffron (Oak Ridge National Laboratory, University of Tennessee - Knoxville)
Xiaobin Lu (Oak Ridge National Laboratory, University of Tennessee - Knoxville)
Diego Venegas-Vargas (Oak Ridge National Laboratory, University of Tennessee - Knoxville)
Rosa Luz Zamora-Peinado (Oak Ridge National Laboratory, University of Tennessee - Knoxville)

Abstract: Neutrinos stand among the least understood particles in the Standard Model. For decades, physicists have used neutrinos from nuclear reactors to study these elusive particles. The intense electron antineutrino flux produced by the beta decays of fission products in nuclear reactors is an effective way to study the antineutrino flux from nuclear reactors and make a precision measurement of the θ_{13} mixing angle. At reactor experiments, antineutrinos are detected via the inverse beta decay (IBD) reaction, and state of the art techniques for event reconstruction are needed to suppress the vast amount of background. In this letter, we explore the possibility of exploiting quantum computing tools for reactor antineutrino event reconstruction.

1 Introduction

Neutrinos are very elusive particles, and some of the last pieces of the Standard Model to be understood. For decades, physicists have used neutrinos from nuclear reactors to study these particles [1, 2, 3]. The intense electron antineutrino flux produced by the beta decays of fission products in nuclear reactors is very useful to study the antineutrino flux from nuclear reactors and to make a precision measurement of the θ_{13} mixing angle [4, 5]. There are several reasons why measuring this angle is one of the priorities in neutrino physics[6]. This measurement will not only represent a step forward in our understanding of the most fundamental properties of nature. It could also hold the key to some of the most critical unanswered questions of our time. For instance, one of the most promising explanations as to why there is more matter than antimatter in the universe is leptogenesis[7], a possible asymmetry between lepton and antilepton creation in the early universe. Finally, one of the most promising prospects for measuring the neutrino mass hierarchy is through the study of θ_{13}-driven oscillations[8], either with an accelerator or with reactor experiments. Furthermore, in addition to the physics program of reactor antineutrino experiments, neutrino detection technology supports nuclear safeguards activities. For example, monitoring a reactor's power through its neutrino emissions is a noninvasive approach that can benefit both reactor operations and nuclear nonproliferation efforts[9, 10, 11].

At reactor experiments, antineutrinos are detected via the inverse beta decay (IBD) reaction: $\bar{\nu_e} + p \rightarrow e^+ + n$. The IBD interaction is reconstructed through the delayed coincidence of pulses generated by the positron annihilation and the neutron capture in the liquid scintillator volume, which is usually a hydrogen-rich material, loaded with an element such as boron or lithium, that has a propensity for capturing neutrons. Requiring a coincidence of the prompt positron light with the delayed neutron capture light allows us to reduce the backgrounds drastically.

Near-surface detectors such as short-baseline antineutrino experiments have to deal with huge backgrounds, which must be suppressed to a large extent, to obtain a good signal to background ratio. Therefore, current and future neutrino experiments need to develop state of the art techniques for IBD candidate selection. An improved IBD selection technique could not only have applications in HEP but, as mentioned before, in nuclear safeguards, as it could hold the potential to monitor fissile reactor content in an almost real-time fashion.

In short, this LOI speculates about computing topics within the context of reactor antineutrino experiments with aspects that may be reformulated to take advantage of the benefits that quantum computation might offer over the next decade or so.

2 Applications

Several applications of quantum computing have been proposed in high-energy physics (HEP). Within the reactor antineutrino experiments, the following areas for application have been identified:

- **Underlying physics and simulation:** One of the most promising applications of quantum computers is simulating quantum systems in a more efficient way than classical methods. An example is the calculation of neutrino oscillations [12]. The authors define gate arrangements that implement the neutral lepton mixing operation and neutrino time evolution in two-, three-, and four-flavor systems in this work. Later, they calculate oscillation probabilities by coherently preparing quantum states within the quantum processing device, time-evolving them unitarily, and performing measurements in the flavor basis, finding excellent agreement with classical calculations.

- **Object/Event reconstruction:** Quantum-assisted algorithms for IBD event reconstruction have been proposed [13]. The algorithm employs a probability distribution in a hyperparameter space of the detector pulses' spatial and time distributions and pairs them according to an "earth-movers distance" metric that has been employed in classical machine learning. In this way, matching the pulses that would reconstruct the IBD interaction is cast to finding the ground state of an Ising Hamiltonian through a quantum annealing device such as D-Wave.

- **Event Selection/Classification:** Classification of events from either the sought-after process (signal) or background is one of the main HEP tasks. The authors of [14] propose the use of quantum computing, in particular, quantum annealing, to classify events between a Higgs decaying to a pair of photons and the background events with two uncorrelated photons. Reactor antineutrino experiments could benefit from these tools not only for background and signal event classification but also by using quantum machine learning for particle identification and pulse shape discrimination, which are the main handles for background suppression in this particular kind of detectors.

3 Conclusion

In this letter, we present a few ideas on how to harness quantum computing power for the analysis and reconstruction of IBD interactions in reactor antineutrino experiments. While the question of whether there will ever be a quantum advantage, and the future of hardware is uncertain, it is still crucial to start identifying algorithms and applications suitable for the noisy intermediate-scale quantum (NISQ) era of computing. A few areas starting from the simulation and calculation of quantum mechanical systems to the analysis of data coming out from reactor antineutrino experiments are outlined here. The hope is to explore these ideas further within the next decade or so and identify which algorithms and physical systems are suitable for maximizing quantum advantage.

References:

[1] J.P. Ochoa-Ricoux. Reactor antineutrinos: Present and future. *Nuclear and Particle Physics Proceedings*, 267-269:116 – 122, 2015. X Latin American Symposium of High Energy Physics.

[2] L.J. Wen, J. Cao, and Y.F. Wang. Reactor neutrino experiments: Present and future. *Annual Review of Nuclear and Particle Science*, 67(1):183–211, Oct 2017.

[3] Carlo Giunti and Thierry Lasserre. ev-scale sterile neutrinos. *Annual Review of Nuclear and Particle Science*, 69(1):163–190, Oct 2019.

[4] C. Zhang, X. Qian, and P. Vogel. Reactor antineutrino anomaly with known13. *Physical Review D*, 87(7), Apr 2013.

[5] Sanjib Kumar Agarwalla, Partha Bagchi, David V. Forero, and Mariam Tortola. Probing non-standard interactions at daya bay, 2014.

[6] H. de Kerret et al. Double Chooz θ_{13} measurement via total neutron capture detection. *Nature Phys.*, 16(5):558–564, 2020.

[7] G.C Branco, R González Felipe, F.R Joaquim, and M.N Rebelo. Leptogenesis, cp violation and neutrino data: what can we learn? *Nuclear Physics B*, 640(1-2):202–232, Sep 2002.

[8] Soo-Bong Kim. Measurement of neutrino mixing angle 13 and mass difference mee2 from reactor antineutrino disappearance in the reno experiment. *Nuclear Physics B*, 908:94 – 115, 2016. Neutrino Oscillations: Celebrating the Nobel Prize in Physics 2015.

[9] Mikaélyan L. A. Borovoi, A. A. Possibilities of the practical use of neutrinos. *Soviet Atomic Energy*, 44:589–592, 1978.

[10] Yeongduk Kim. Detection of antineutrinos for reactor monitoring. *Nuclear Engineering and Technology*, 48(2):285 – 292, 2016.

[11] J.C. Anjos et al. Using Neutrinos to Monitor Nuclear Reactors: the Angra Neutrino Experiment, Simulation and Detector Status. *Nucl. Part. Phys. Proc.*, 267-269:108–115, 2015.

[12] C. A. Argüelles and B. J. P. Jones. Neutrino oscillations in a quantum processor. *Physical Review Research*, 1(3), Dec 2019.

[13] Galindo-Uribarri A. Delgado, A. et al. Machine learning applications for reactor antineutrino event detection at prospect. https://indico.slac.stanford.edu/event/371/contributions/1207/attachments/539/863/NPMLWorkshop_PROSPECT_ORNL.pdf, 2020.

[14] Alex Mott, Joshua Job, Jean-Roch Vlimant, Daniel Lidar, and Maria Spiropulu. Solving a higgs optimization problem with quantum annealing for machine learning. *Nature*, 550, 2017.