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Enabling Measurements of Qubit Errors at NEXUS

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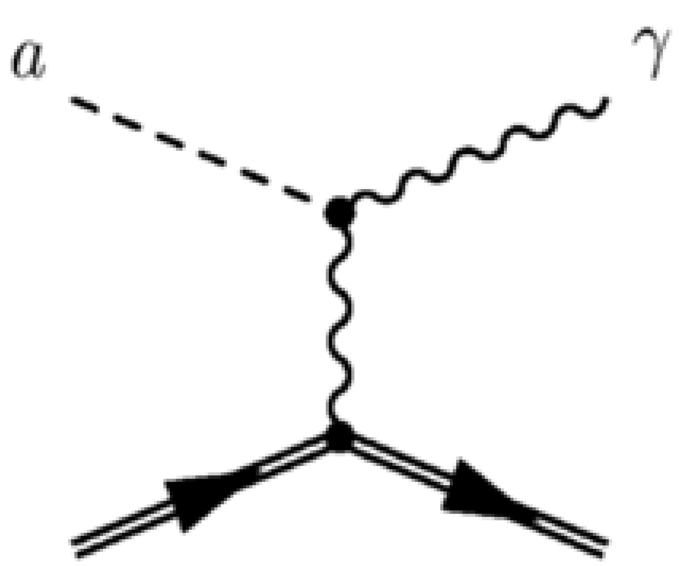
Motivation

As qubit technology progresses, one intriguing application involves their use as low noise single photon detectors. By measuring how the readout frequency of a resonator coupled to the qubit shifts in the presence of a photon, faint signals can be distinguished from mK-scale thermal noise. With this sensitivity, phenomena such as axion conversion to photons may be detectable.

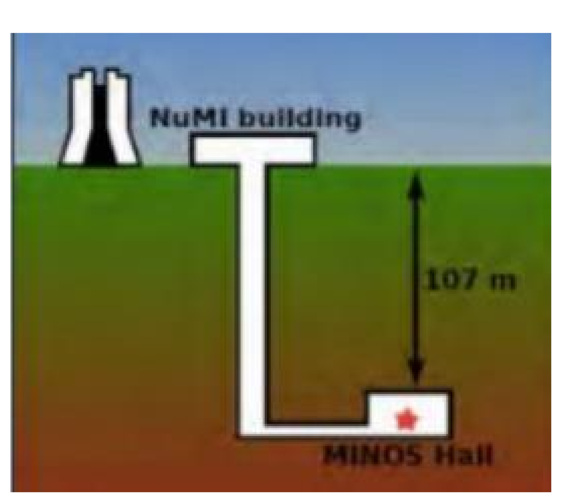


Axion conversion to photon: ongoing and future experiments will explore regions of axion parameter space that correspond to axion-dominated dark matter.

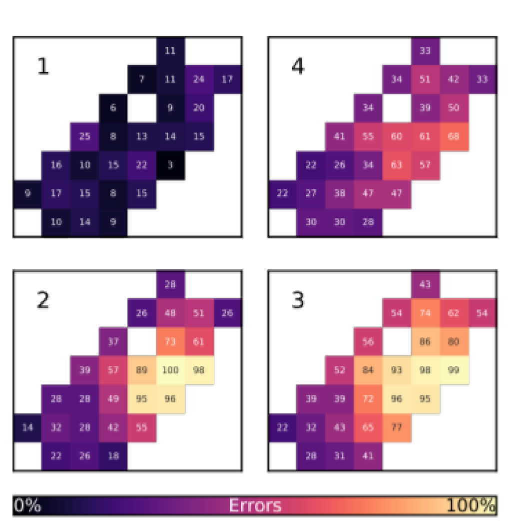
Though they have long been viewed a promising dark matter candidate, some DM-plausible axion mass values have thus far been difficult to probe via conventional photon counting techniques due to weak signal strength relative to noise.

Objective

Recent scholarship suggests that ionizing radiation may cause major issues in qubits, namely decoherence and 'catastrophic' correlated errors across time and space. Compromised coherence constrains all qubit applications, while such multi-qubit errors break current error-correction algorithms. We are using NEXUS—Northwestern EXperimental Underground Site at Fermilab—to measure the impact of a low-radiation environment on qubit experiments. If a material difference in coherence time and/or error rate is detected, future qubit applications may need to be designed with such conclusions in mind.



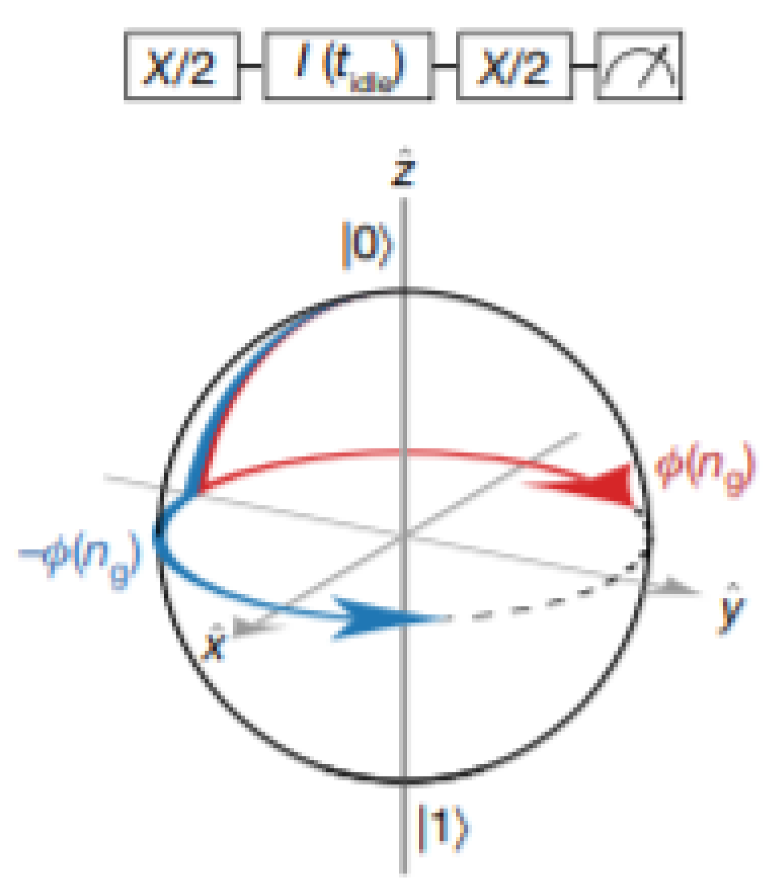
Left: Schematic view of NEXUS featuring an estimated insulation equal to ~300 m of water.



Right: Example of an error-burst event [3], thought to be caused by energy deposition. Note the spatial and temporal correlation (1-4 denoting time slices).

Qubit Spectroscopy

To investigate these errors, we prepare and monitor quantum states. By transmitting tailored signals across the feedline shared by our 4 qubit-resonator pairs, we can identify errors, track their correlations, and monitor their impact on coherence time. The figure below is taken from a collaborator's paper [1] and depicts a set of pulses they employed; we soon will repeat the procedure using precisely the same chip. This controlled study should ensure that any differences in error rate and associated deleterious effects will represent evidence to quantify the impact of radiation shielding on qubit operations.



This panel [1] depicts a pulse sequence we will perform in which a qubit plays the role of 'listener' for charge bursts indicative of energy deposition by ionizing radiation. It is prepared in the |0> state and induced to transition to the |1> state via a tuned pulse-idle-pulse sequence. The rate of time evolution about the Bloch sphere between the first and second pulse depends on the offset charge on the qubit, which remains roughly constant under ordinary operation. When a burst occurs, however, the pulse sequence will result in altered |1> occupancy rates due to the new charge level. Above ground (with the same qubits) a strong correlation was observed between large charge jumps in nearby qubits, and the rate of bursts was noted. If that correlation persists yet error events are less frequent, it is likely that ionizing radiation is noticeably harming qubit function. Additionally, measurements of coherence time during bursts will be conducted with the same equipment.

Acknowledgements

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References

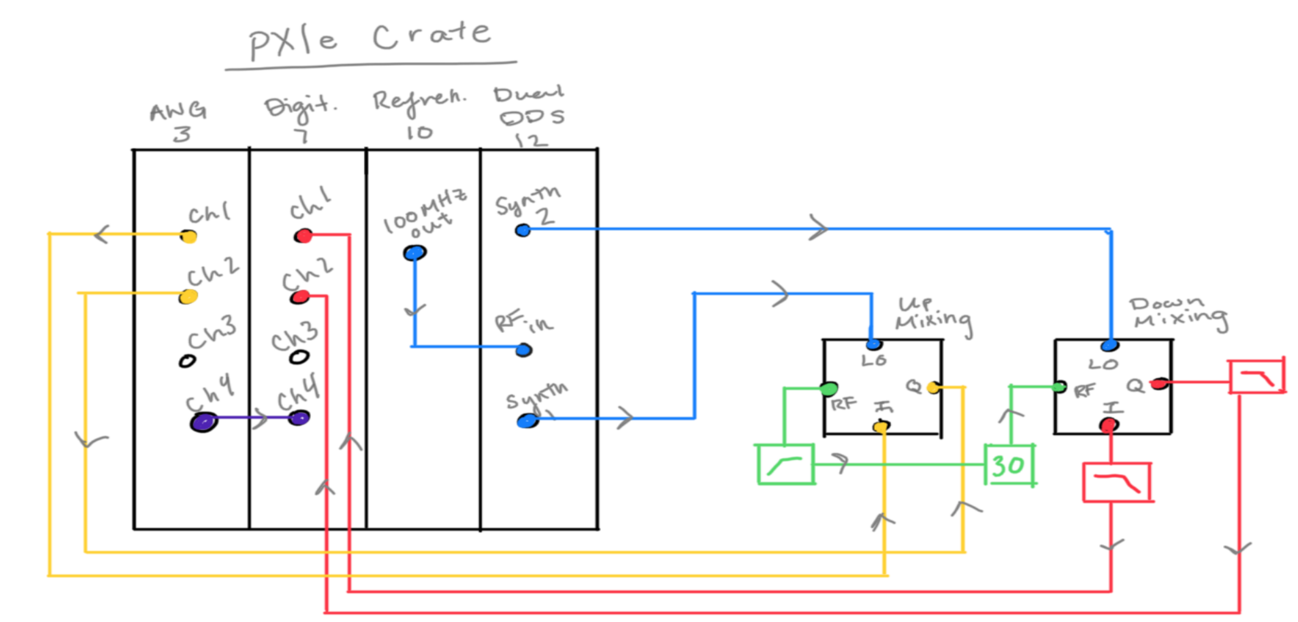
[1] Wilen, C.D. *et al.* Correlated charge noise and relaxation errors in superconducting qubits. *Nature* **594**, 369–373 (2021). https://doi.org/10.1038/s41586-021-03557-5

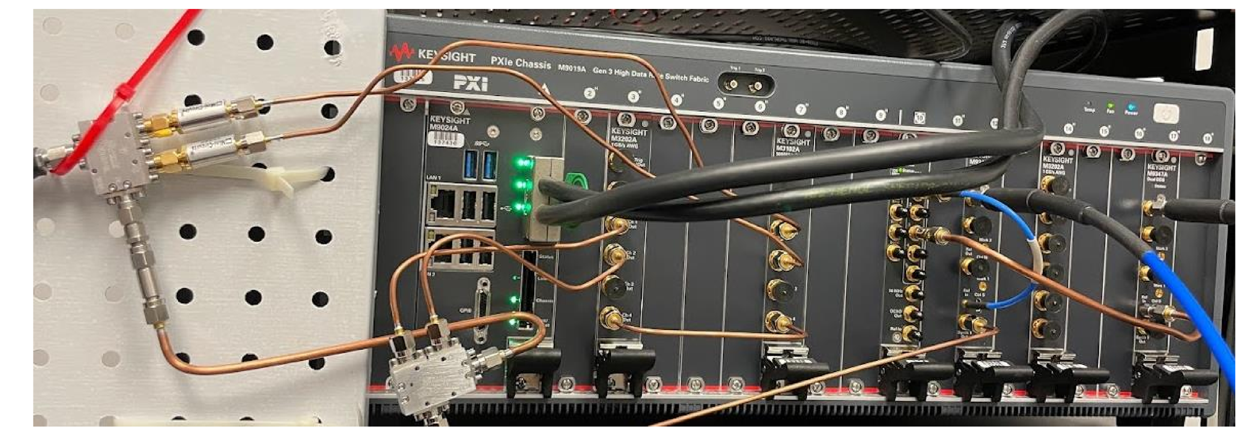
[2] Krantz, P. *et al.* A Quantum Engineer's Guide to Superconducting Qubits. *Applied Physics Reviews* **6**, 021318 (2019). http://dx.doi.org/10.1063/1.5089550

[3] McEwen, M. *et al.* Resolving catastrophic error bursts from cosmic rays in large arrays of superconducting qubits, arXiv:2104.05219

[4] Bratrud, G., Bowring, D. Qubit Signal Processing and the Search for Dark Matter, FERMILAB-POSTER-21-109-STUDENT

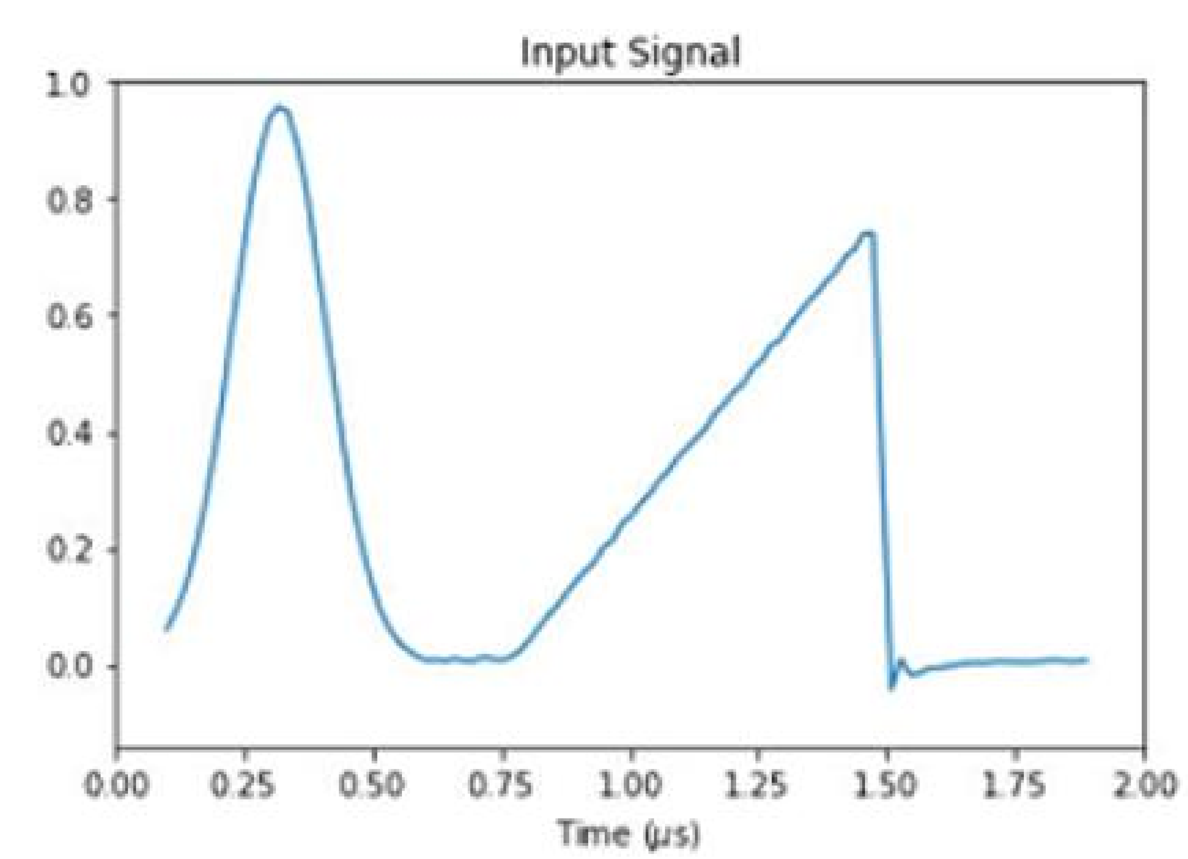
Measurement Methods





The setup [4] used to configure the qubit control electronics. Signal flows from the Keysight arbitrary waveform generator to an I/Q mixer which translates the pulse frequency into the qubit's transition or resonator's readout frequency using the Keysight DDS synthesizer as a local oscillator. From there, any response is downmixed and digitized to be stored and analyzed later.

But how do we send these pulses? We developed control protocols for the 'warm electronics' shown above. Each instrument was tested and configured to—as an ensemble—generate arbitrary pulses such as gaussian-envelope wave packets that are used to prepare desired states or readout pulses to measure them. The pictured configuration allowed us to test input and output procedures and verify that everything is working as intended before adding the fridge and qubits into the loop. The 30 dB attenuator between the mixers acts as a stand-in for the qubit payload in this test setup.



A plot of a custom waveform sent directly from the AWG to the Digitizer simulating an input and output cycle. With this verification successful, we are prepared to execute pulsed qubit spectroscopy. All the electronic equipment is controllable programmatically: arbitrary pulses can be sent to the qubit to set and/or measure the qubit energy levels and their excess charges.