Quantum Information Science and Underground Facilities

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INTRODUCTION

As both nuclear physics and particle physics involve the quantum interactions of many sub-atomic particles, there has always existed a strong interplay between these fields and the study of quantum physics and quantum information systems (QIS). This interplay has accelerated in recent years, particularly with the emergence of new, highly sensitive technologies, nascent access to quantum computing environments at the O(10)-O(100)-bit scale, and the use of coherence and entanglement to enhance sensitivity to novel and exotic phenomena. One unusual area of interplay between the two disciplines that has recently emerged is the role of background radiation and background mitigation on highly sensitive systems such as qubits.

CURRENT STATUS

In order to make quantum computing a viable and usable technology, the underlying units of computation –qubits– must exhibit high fidelity and long coherence times. Over the past two decades, advances in device design, fabrication, and materials have increased coherence times by almost six orders of magnitude [1]. Nonetheless, to realize the full promise of quantum computing, far longer coherence times will be needed to achieve the operational fidelity required for fault-tolerant computation. Coherence for superconducting qubits can be spoiled by an excess density of quasi-particles, and quasi-particle densities far exceed what is naively expected from thermal equilibrium. Recent measurements made by several groups [2, 3, 4, 5] have shown that one creeping contribution to quasi-particle poisoning appears due to ionizing radiation stemming from external gamma radiation, cosmic rays, and radiogenic contamination of materials surrounding the qubit. This source of quasi-particle poisoning is particularly worrisome for QIS applications, since ionizing radiation appears to affect multiple qubits simultaneously [3, 4]. Since quantum error correction (QEC) schemes –necessary for scaling quantum computing– rely on qubits to exhibit random, uncorrelated errors, correlated error sources would render such schemes ineffective. Ionizing radiation has been deemed "catastrophic" because of its ability to potentially circumvent traditional QEC algorithms.

Fortunately, a number of techniques are being devised to reduce the impact of radiation. These include spatially distributed error correction schemes [6], material engineering to promote phonon down-conversion [7, 8], and developing a more comprehensive understanding of the underlying microscopic physics that leads to quasi-particle poisoning [9, 10]. As cosmic ray radiation is a non-negligible portion of the environmental radiation, underground facilities may also provide a unique resource for studying quasi-particle poisoning in radiation-quiet environments. Here "underground facilities" is a catchall for the decades of experience in the nuclear and particle physics communities for background mitigation and suppression. Underground laboratories specifically may offer perhaps one of the only ways to effectively reduce the cosmic ray flux impingent upon a multi-qubit system. Although precise models of how cosmic rays impact multi-qubit systems are still being studied, preliminary measurements on similar systems have shown that significant overburden could improve qubit performance [5, 11].

Underground facilities could be excellent locations for studying qubit systems in low background environments, with relatively modest investments in infrastructure and resources. Small facilities have already started to emerge in both deep and shallow sites, such as FERMILAB, SNOLAB, Pacific Northwest National Laboratory, and Gran Sasso. As qubit systems operate at cryogenic temperatures, such facilities would need to sustain use of dilution refrigerators underground. Such systems are already in place for several dark matter experiments that operate at cryogenic temperatures (e.g. EDELWEISS [13]).

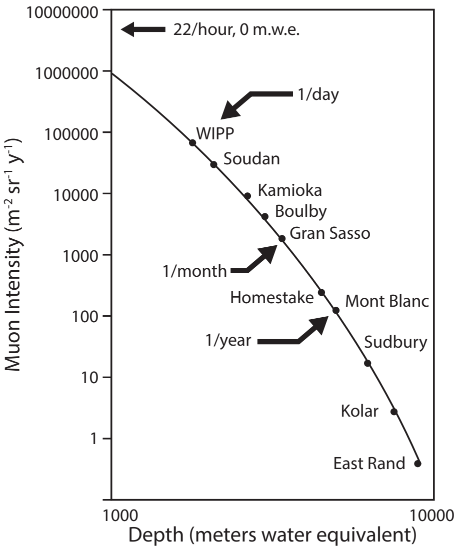

FIGURE 1. Vertical muon intensity as a function of depth (in meters water equivalent). Current (circle) and former (triangle) underground laboratory depths are indicated along the curve. Arrows indicate expected muon rate for a 1 cm × 1 cm qubit chip, scaled by the surface rate. Figure from Patrick Harrington (MIT), adapted from [12].

CONCLUSION

As quantum computing systems advance in computational power and capability, radioactivity is likely to play an ever-increasing role in their performance. Underground facilities, coupled with decades of experience of running sensitive, low-background experiments underground, offer a unique space to study how such systems behave in radiation-quiet environments. These laboratories can also be a catalyst for further collaboration between the fields of particle physics, nuclear physics and QIS.

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