An Intersection of Radiation Detection and Superconducting Electronics

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Abstract. Many modern quantum devices are subject to lower energy events due to the low energy bandgap in these devices. Experimentalists search for dark matter with masses below the proton are targeting these technologies for light dark matter searches. Quantum computing and sensors are limited by coupling to sources of energy in the environment, and dark matter searches seek to understand and control coupling to sources of energy in the environment. The background sources of energy in the environment include nuclear and high-energy radiation, photons from radiation interactions in materials around the detectors, physical stress in the detector, infrared leakage from higher temperature baths, and vibrations. The complementary research threads between quantum computing and sensor development and dark matter searches will lead to productive multidisciplinary research between these two active fields over the next decade.

INTRODUCTION

Detectors rely on bandgaps in systems so that some number of transitions from states below the bandgap to states above the bandgap defines an 'event' in the detector. An example in semiconductor detectors is the excitation of electron-hole conduction pairs from environmental interactions. The bandgap then becomes the minimum threshold achievable, that is there must be at least one transition to detect an event. In semiconductors, the bandgap to excite one electron-hole pair in the conduction band is typically about 1 eV. Current light dark matter detectors are achieving single transition thresholds and studying the menagerie of environmental backgrounds associated with these energies. The desired sensitivity to light dark matter candidates in future searches requires developing lower threshold detectors, which must rely on lower bandgap materials.

Research into the high-temperature couplings to nature has been a focus in physics research and has strongly contributed to the development of astrophysics and subatomic physics. Researchers over the last century and a half have developed exquisite detectors to study the detailed events that occur in nature at atomic and nuclear energy scales. By studying the radiation backgrounds in nature at high-energy, we test the limits of our understanding of the source, transport, and detection of these phenomena in nature. As we look towards developing lower threshold detectors, this detailed event-by-event understanding of the backgrounds also needs development. In this way, lower threshold detectors will rely on the current generation of detectors developing an understanding of environmental backgrounds above 1 eV to bootstrap studies of backgrounds below this energy scale. There is an important relationship between backgrounds understanding, material science, and detector development.

For the rest of this proceeding, I will take superconducting devices as an example low energy system. Superconducting qubits are leading devices in the race to build performant quantum computers. Superconducting devices such as Josephsen junctions are fundamental building blocks for a variety of modern quantum devices. In superconductors, electrons are bound into Cooper pairs by their mutual attraction in some materials. This is a weak bond and the strength of this bond can be quantified in the superconducting gap. For low temperature superconductors, this gap is tens of microelectron volts, four orders of magnitude below typical semiconductors.

As reported from dark matter searches such as SuperCDMS and Edelweiss, ionizing radiation impacts low temperature substrates and causes a cascade of phonon activity as the energy is absorbed and partitions into the available modes. These phonons become ballistic and travel throughout the substrate on timescales of 10–1000 microseconds, depending on the thermal coupling of the substrate and the quantity and types of metals patterned on the substrate. These ballistic phonons have more energy than the superconducting gap of, say, aluminum, and they efficiently break Cooper pairs creating non-thermal quasiparticles.

Thus, ionizing radiation from background radioactivity can simultaneously cause disruptions in all superconducting devices that share a substrate. Correlated errors from ionizing radiation are not even restricted to a single substrate. Alpha decays typically occur on the surfaces of materials and the alpha can straggle from a few 10s of micrometers through a surface layer of one substrate and impact a neighboring substrate. Gamma rays can Compton scatter and deposit energy in multiple substrates simultaneously, even when the substrates are separated by space and materials.

Beta rays can similarly create bremsstrahlung photons that travel through space and materials leading to simultaneous errors in multiple substrates. Muons created in high-energy cosmic-ray interactions in the atmosphere can penetrate entire cryostats, and kilometers of earth, creating a line of correlated errors. Furthermore, much lower energy photons can be produced in coherent bursts, such as the transition radiation and Cherenkov radiation emitted by matter in response to ionizing radiation.

Not only can simultaneous energy depositions result from a single ionizing particle emitted during radioactive decays, but also multiple ionizing particles can be created during events and cause simultaneous events in single or multiple substrates. These radioactive decays emit multiple particles in nuclear de-excitation, chains of nuclear decays with short half-lives, or high-energy particle cascades spread over surface areas with $\sim$ 100-m diameters [1].

For quantum computing these correlated errors will defeat many of the error correction algorithms currently under development. Error correction is an integral part of modern quantum computing, but the basic assumption by many algorithms is that the errors are uncorrelated. The timescale to detect these as "correlated" or "uncorrelated" is set by the qubit technology and the calculation and readout times. The impact of ionizing radiation will limit the quality of quantum computation, restrict the typical number of allowed gates in computation, and reduce the flexibility in readout technologies. Ionizing radiation concerns will be a fundamental design consideration in many aspects of quantum computing.

EXAMPLE FROM RECENT MEASUREMENTS OF THE GOOGLE SYCAMORE QUANTUM PROCESSOR

Quantum devices are changing information technologies such as computation, sensors, and communication. Some quantum devices are operated at low temperatures, near absolute zero, to take advantage of the quantum properties that emerge at these temperatures, again superconductivity is an example. However, the unexpected density of quasiparticles in superconducting films at low temperature is an impediment to improving the performance of some superconducting devices [2]. For example, the density of quasiparticles is a barrier to the performance of many superconducting qubits. This excess of athermal quasiparticles is typically called "quasiparticle poisoning" and has driven device development in quantum computing to attempt to avoid the sensitivity to this excess energy, which is attributed to couplings to the environment.

Researchers have successfully reproduced the results of superconducting radiation detector developers by observing high-energy events inside modern quantum processors [3]. This result, hereafter called the McEwen result, uses a modern Google Sycamore quantum processor and demonstrates a technique to detect events that deposit significant energy in the processor substrate. This energy eventually causes non-unitary de-excitation of the qubits for at least 100 ms. The energy depositions identified by their technique propagate across the substrate causing correlated errors in a growing number of qubits. Eventually, all of the qubits on the processor malfunctioned at the same time due to the excess energy deposition, hence the inclusion of "catastrophic errors" in the title of the McEwen result. These results generally agree with decades of detector development results, in fact the tungsten TESs of SuperCDMS often saturate, that is they go normal during some high-energy events or due to energy from drifting charges. If superconducting technologies are disrupted by a temporary transition to the normal state, then they will be disrupted by environmental radiation backgrounds.

The McEwen result quotes a rate of $\sim$ 0.1 Hz for the events they identify, and a breakdown into gamma rays and cosmic rays environmental rates is given in the supplementary material. The rates in the substrate are identified as 1/(38 s) for cosmic rays and 1/(7.6 s) for gamma rays, calibrated with a smaller detector. These rates are typical of the $\sim$ 0.5 g substrate used for the processor.

There are a variety of processes in the environment that can contribute to this rate and here we do not attempt to contribute the rate to any one process or build a background budget, but to elucidate the rich variety of phenomena and environmental couplings that can contribute to such a rate. This quoted rate of 0.1 Hz/g is typical of unshielded materials on the surface of the earth, and often can be from a variety of environmental sources. For example, this rate can be produced by uranium, thorium, and potassium contamination typical of materials used for electronics, specifically the cables, connectors, and some discrete components are the most common source of radioactivity in cryogenic assemblies [4]. Surface alpha rates near 0.1 Hz across these areas may be achieved by surface contamination of (typically) radon daughters, but surface alpha rates are typically below $\sim$1 α/cm^2/hr for silicon substrates unless they have been contaminated [5]. One interesting component is the indium used to bump-bond two silicon substrates together in the Sycamore processor described in the McEwen result. They state that the indium bump bonds are 5 μm tall and cover $\sim$ 15% of the surface of the device. This is $\sim$ 17 milligrams of indium with an activity of 1/(225 s), which is also approaching the rates observed in the device. All of these sources of environmental coupling will be present in the devices near the observed rates of *catastrophic* errors. Remember that the catastrophic errors counted in the McEwen rate are those that impact most qubits, but the energy couplings to nature tend to increase in rate at lower energies [6] so one expects a higher rate of these non-unitary error events that only effect a few qubits simultaneously.

These rates are significant enough to impact the performance goals of quantum computers based on superconducting qubits. Radiation limits the coherence time of individual qubits, and the total calculation time because the events create coherent errors in the qubits, which most error correction does not address. Thus, from the cables and connectors, to the site overburden for the quantum device, to the materials used to create the device, all aspects of these devices should include considerations of environmental radiation as the processors scale in size and improve in performance.

LOW-MASS DARK MATTER BACKGROUNDS

Low-energy quantum systems are attractive technologies for low-mass dark matter searches, a growing priority in high-energy physics. Weakly Interacting Massive Particles (WIMPs) are a leading hypothesis for the nature of the dark matter that make up $\sim 85\%$ of the matter in the Universe. A new particle that decouples from the Big Bang earlier than the hadronic matter would allow time for initial perturbations to grow into the galaxies that exist today. Experimental collaborations searching for WIMPs over the past two decades have not reported any confirmed signals, despite sensitivity increases of many orders of magnitudes over the past four decades. These searches were focused on masses near $\sim$100 GeV/c^2 and the community has recently prioritized searches well below this mass range in light of recent theoretical interest and because light particles would not have been detected in the previous searches; the expected energy deposition is below the threshold of historical WIMP searches. Thus, technologies that can result in particle detectors with much lower energy thresholds are also a priority. The Department of Energy released two coupled statements of basic research need prioritizing lower mass dark matter searches and detectors with meV thresholds to enable these searches [7]. As dark matter researchers achieve lower thresholds, they have identified the growing challenge of backgrounds understanding and control in this new regime and this background challenge is critical to the success of dark matter searches in this new energy window.

Many particle detectors are limited by the subatomic mechanisms for generating currents in readout electronics, typically based on ionization. In fact, this split in particle detection is so entrenched in physics we split radiation detection into "ionizing detection" and "non-ionizing" detection. Lower bandgaps can be created in materials, but for most materials used in particle detection, the ionization bandgap is typically $\sim$1–10 electron volts. This corresponds to a temperature of 10,000 K, so blackbody radiation at 300 K should not ionize materials. The spectrum of blackbody radiation, along with some convenient energy scales is shown in Figure 1. The observation, and investigation, of the ionization in matter at room temperature was a major part of the development of the fields of nuclear and particle physics. However, the energy required to ionize most materials is higher than the desired threshold for light dark matter detector development. New technologies driven by the development of quantum science and technology have allowed dreams of a new energy window between $\sim$1–1000 meV that has not been studied for environmental couplings using particle radiation detectors, and this energy range may contain the key to understanding the nature of dark matter. Traditional direct searches for dark matter are rare event searches that employ the low radioactivity background techniques to control environmental couplings to the level of 1 nuclear event per kilogram per year [8] and below 1 event per kilogram per day for electron scattering events [9]. These rates are quoted for the integrated rate of events above the energy threshold, typically around 1 keV. Driven by the search for light dark matter, researchers have explored down to $\sim$ 1 eV and are reporting excesses of events above the backgrounds expected by extrapolating from higher energies [6]. The hypotheses for these events includes lower energy photons from radiation interactions in materials around the detectors, physical stress in the detector, infrared leakage from higher temperature baths, and vibrations. Dark matter researchers are investigating all of these potential couplings to the environment and have demonstrated progress in identifying and controlling some of these couplings. This area of background understanding and control will continue as an item at the forefront of this dark matter research.

CONCLUSION

The search for light dark matter has driven high-energy physics researchers to design radiation detectors with low energy thresholds, demonstrated at the atomic scale of electron volts with future requirements for even lower energies [7]. Superconducting circuits have been a component of low temperature radiation detection and are attractive

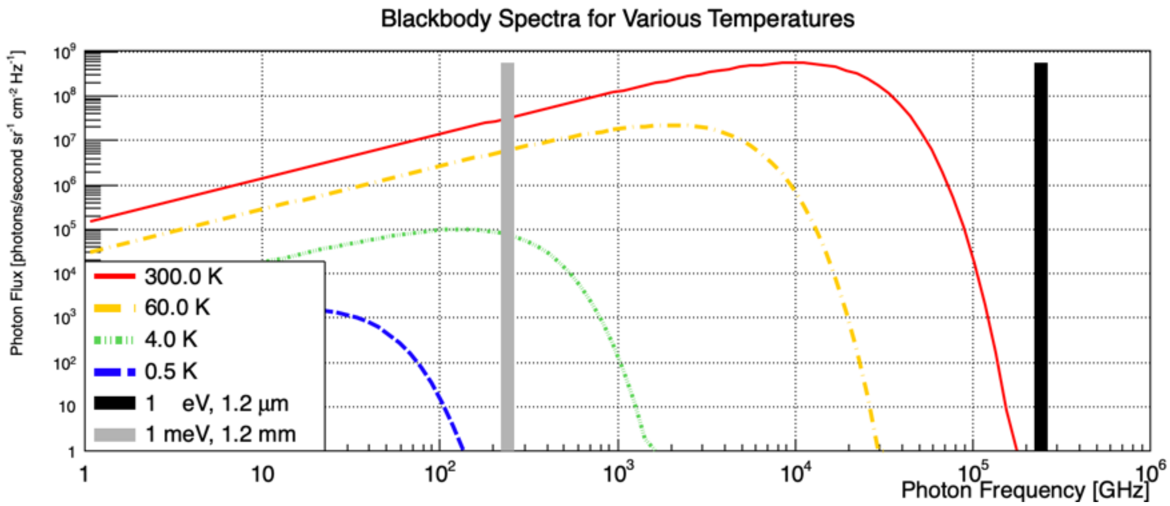

FIGURE 1. The blackbody spectrum at room temperature is not a significant background for most ionizing radiation detector technologies. However, lower energy photodetectors and technologies that rely on low-temperature superconducting bandgaps near 1 meV, such as dark matter detectors and superconducting qubits, must control infrared leakage impacting device performance. This is an example of the shared environmental coupling challenge between superconducting electronics development and light dark matter searches.

devices for this low threshold requirement because the energy to break a cooper pair and create a quasiparticle is typically less than a thousandth of an electron volt. The particle physics community increasingly leverages superconducting devices as sensors, and there is now a convergence in requirements between particle physics and the superconducting electronics field [10, 11].

This alignment in requirements is quite simple, quantum engineers would like to understand (and control) every quasiparticle in superconductors at low temperature for better device performance, and particle physicists wish to understand nature at the low energies accessible via counting fewer and fewer quasiparticles. Fundamentally, both superconducting quantum circuit designers and particle physicists wish to develop technologies and theory to better understand the density of quasiparticles in millikelvin superconducting films over the next decade. This specific alignment of goals in superconducting electronics and light dark matter will result in scientific and technological innovation over the next decade, similar to the convergence between semiconductor particle detectors and semiconductor electronics in the last century.

The high-energy physics understanding of the sources, transport, and fate of energy at low temperature will have an impact on the performance of quantum circuits. In turn, the high-energy physics community will benefit from improvements to device manufacturing techniques that will be made once the sources of environmental noise are separated from the sources intrinsic to the device construction. The drive to develop quantum sensors and quantum computers has already produced a number of devices that are under consideration for high-energy physics experiments, including the search for dark matter. In dark matter research, we will either discover the dark matter as a fundamental limit from nature for superconducting devices, or we will rule out light dark matter and develop techniques to control the backgrounds interfering with the performance of superconducting devices.

ACKNOWLEDGMENTS

The author would like to acknowledge the extraordinary dedication and talent of the scientific, technical, operational, and management staff at SNOLAB, as well as the contributions of the scientific users. SNOLAB is a world-class research facility due to their efforts over the past few decades. SNOLAB operations are supported by the Canada Foundation for Innovation and the Province of Ontario, with underground access provided by Vale Canada Limited at the Creighton mine site.

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