Coupling Experiment and Simulation to Model Non-Equilibrium Quasiparticle Dynamics in Superconductors

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Thematic Areas: (check all that apply ☐/■)

■ (CF1) Dark Matter: Particle Like
■ (CF2) Dark Matter: Wavelike
■ (IF1) Quantum Sensors
■ (IF2) Photon Detectors
■ (IF9) Cross Cutting and Systems Integration
■ (UF02) Underground Facilities for Cosmic Frontier
■ (UF05) Synergistic Research

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Abstract

In superconducting devices, broken Cooper pairs (quasiparticles) may be considered signal (e.g., transition edge sensors, kinetic inductance detectors) or noise (e.g., quantum sensors, qubits). In order to improve design for these devices, a better understanding of quasiparticle production and transport is required. We propose a multi-disciplinary collaboration to perform measurements in low-background facilities that will be used to improve modeling and simulation tools, suggest new measurements, and drive the design of future improved devices.

Broken Cooper pairs, or quasiparticles (QPs), are an important source of loss and decoherence in superconducting devices. This loss mechanism underpins devices like transition edge sensors, which are currently used in low-threshold dark matter searches [1, 2]. Alternatively, this loss can be problematic in devices such as superconducting qubits, which benefit from long coherence times [3, 4]. Whether nonequilibrium QPs are considered a bug or a feature in any given superconducting device, we posit that a broad range of the particle physics community would benefit, directly or indirectly, from an improved understanding of the mechanisms by which QPs instantiate, propagate, diffuse, and decay. Others outside of HEP, such as researchers in condensed matter and quantum information science, also stand to benefit.

Naively, when a superconducting device is in equilibrium with its cryogenic environment well below the superconducting critical temperature, one expects an exponentially small density of thermally excited QPs. However, a large body of work across a range of superconducting devices reveals the presence of a high density of QPs far in excesss of that expected at thermal equilibrium [5, 6, 7, 8, 9]. Explaining the origin of these nonequilibrium QPs and mitigating them is an ongoing concern across multiple STEM disciplines. For many devices, a rough requirement is that charge and phonons from MeV-scale energy deposits cannot create a single QP in a superconducting resonator, **corresponding to an energy rejection factor of one part in 10^9**. Understanding the myriad ways in which these high-energy events couple into superconducting devices thus requires precise modeling of the microphysical processes which mediate pair-breaking, with the goal of tracking down the minute fraction of the initial energy deposit creating excess QP density and spoiling the state of the superconductor. Conversely, various applications may seek to maximize one mode of coupling (e.g. IR photons) while minimizing others (e.g. phonons) in order to achieve sensitivity to a desired set of single quanta without becoming susceptible to a large excess QP background.

Environmental radioactivity has been shown to limit the performance of superconducting devices through dissipative QP generation [10, 11], and ionizing radiation specifically has been recently proposed as a QP generating mechanism [12, 13, 14]. Cosmic rays – and also the decay products of the radioactive contaminants naturally present in the laboratory environment – can deposit energy in the superconducting circuit or, more probably, in the substrate on which the circuit is fabricated. This deposited energy is converted into charge and phonons, which diffuse through the substrate and can be absorbed by the superconducting circuit.

This phenomenon is the working principle of many physics detectors [15, 16, 17, 18, 19, 20, 21] and has several important consequences. Energy absorption increases the density of QPs, thus limiting the coherence time of the device under test. For example, Ref [13] recently showed that, if not suppressed with proper shields, environmental radioactivity could prevent qubit coherence times longer than milliseconds. In addition, such events can cause simultaneous flips of many qubits following an energy deposit in the substrate, which is a serious complication for current quantum error correction strategies that assume spatially uncorrelated errors in the qubits belonging to the same matrix [14]. In Ref [14], the operation of superconducting circuits in a deep underground laboratory reduced the number of QP bursts by a factor of $\sim$50 resulting in an improvement of the devices' internal quality factor by 2–3$\times$. This seems to suggest that the shielding of environmental radioactivity – and, concurrently, an improved understanding of nonequilibrium QP dynamics in these contexts – will be a growing concern for multiple physics disciplines.

One area where nonequilibrium QP dynamics will be of concern is quantum sensing, for HEP and for other fields. For example, there is growing interest in the use of superconducting qubits to search for axion dark matter [22, 23, 24, 25]. In this context, environmental sources of device decoherence impose lower limits on statistical errors associated with signal integration. But also, there is evidence to suggest that QP bursts may impart energy to superconducting qubits, leading to spurious state transitions – an extra source of systematic error [4]. (In the context of superconducting qubit arrays that are being pursued for fault-tolerant quantum computing, burst events from high-energy gamma rays or cosmic ray muons that are absorbed in the substrate generate nonequilibrium QPs that couple simultaneously to multiple qubits over $\sim$mm length scales, leading to spatially correlated bit-flip errors that are particularly damaging for proposed quantum error correction protocols.

In addition, many experiments which probe CMB [26, 27], real-time astrophysical spectroscopy [28, 29], and particle dark matter physics [30, 31, 32, 33] employ superconducting resonators and trap-assisted TESs to detect absorbed power either directly from photons or from phonons generated in the target crystal. In the former case, coupling of phonons into the sensors causes a power resolution degradation in a similar manner to decoherence in qubits [34]. In the latter case, maximizing the phonon coupling to the sensor, and understanding spatial quasiparticle diffusion and energy transport, are crucial to maximizing energy sensitivity to achieve thresholds comparable to tens of quasiparticles worth of energy. Both applications need improved tools to inform detector design in order to better optimize their sensors for a given application.

All together, the above considerations have led us to identify a number of related opportunities for HEP, and for the broader physics community:

1. More theoretical work is needed to understand QP dynamics across a broader range of materials, interfaces and environments [35, 3, 36]. Existing theoretical frameworks are not suited to modeling three-dimensional kinematics of quasiparticle-phonon interactions in realistic physical systems. We as a community must support broader education in superconductor theory and the further development of scattering theory for quasiparticle-phonon interactions.
2. Common simulation tools have not kept pace with experimental developments in quantum sensing. Mature quantum computing research requires open-source simulation packages (similar to GEANT for particle physics, SPICE/Cadence for semiconductors, and multiphysics packages for E&M) to streamline the design process and allow solved problems to be modeled in simulations.
3. Integrated microfabrication efforts are required to realize test devices and mitigation solutions motivated by items 1 and 2.
4. A set of well-controlled and characterized facilities to separate external environmental coupling from intrinsic device performance. Critical to this are standards and metrology for ionizing radiation, non-ionizing radiation, stray electromagnetic fields, and vibration. With robust standards and metrology, experiments can be better compared to each other and to theory and simulations for both particle physics and superconducting device development.

We believe that these challenges are best addressed by a multidisciplinary collaboration. Next-generation experiments and metrological techniques will require a more robust understanding of these processes across a range of disciplines and skills. More understanding is needed of the interplay between ionizing radiation, phonon dynamics, and quasiparticle bursts in superconducting sensors. The intent of this LOI is to bring together leading experts from the pertinent field to write a white paper summarizing current understanding of each of the points outlined above, and reach a consensus on the best path forward to enhancing collaboration going forward.

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