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DEMETRA: Suppression of the Relaxation Induced by Radioactivity in Superconducting Qubits

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Abstract
Non-equilibrium quasiparticles can deteriorate the performance of superconducting qubits by reducing their coherence. We are investigating a source of quasiparticles that has been too long neglected, namely radioactivity: cosmic rays, environmental radioactivity and contaminants in the materials can all generate phonons of energy sufficient to break Cooper pairs and thus increase the number of quasiparticles. In this contribution, we describe the status of the project and its perspectives.

Keywords Quantum bits · Kinetic inductance detectors · Radioactivity

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1 Superconducting Quantum Bits

In the last decades, superconducting circuits have emerged as one of the leading technologies for the development of quantum processors [1,2]. Complex circuits can be realized using simple elements such as inductors, capacitors, superconducting cables, radio-frequency waveguides and Josephson junctions. The last component allows to introduce a controlled source of nonlinearity in the circuit, a fundamental requirement for the implementation of an efficient two-level quantum system. Thus, one of the reasons why superconducting circuits are so attractive, is the ease in designing and fabricating low-cost devices, exploiting technologies such as thin-film deposition or lithography. On the other hand, compared to other qubits technologies, superconducting circuits suffer from a shorter coherence time. For the purpose of quantum computing, qubits should feature a coherence time much longer than the gate lengths (10–100 ns for superconducting circuits). Today, typical coherence times of $\sim 100\,\mu s$ already allow almost 10^4 operations [3]. The goal of the next generation devices is to surpass this value by at least one order of magnitude by reaching a coherence time of few milliseconds while preserving a high readout fidelity and a short gate time.

Many phenomena can be responsible for decoherence: dielectric two-level defects [4,5], adsorbed paramagnetic molecules at the interfaces [6], Abrikosov vortices trapped in the superconducting film of the electrodes [7] and quasiparticles [8,9].

All of these sources are subject of an intense research and development activity, but quasiparticles in particular have often emerged as the main contribution to decoherence, especially in high impedance circuits [10–12]. With the DEMETRA project (**DE**coherence **M**itigation through **E**nvironmen**T**al **R**adioactivity **A**batement), we plan to investigate a longtime neglected source of quasiparticles: environmental radioactivity.

2 Radioactivity and Quasiparticles

To understand the potential impact of radioactivity on superconducting qubits, it is worth describing their physical implementation. The electrical circuit that acts as two-level quantum system is fabricated by depositing a superconducting film featuring a typical thickness of tens of nm. Such a thin material is almost transparent to most of the radioactive sources, with the exception of direct interactions in the superconductor due for example to infrared photons or scattering particles.

On the other hand, superconducting circuits are usually deposited on silicon or sapphire substrates featuring surfaces of several cm^2 and thicknesses of hundreds of μm. Due to its large size, the substrate cannot be immune to radioactivity. Radioactive interactions release energy in the substrate, producing phonons. Phonons can travel in the substrate until they are eventually absorbed by the qubit, breaking Cooper pairs into quasiparticles (Fig. 1).

Today, the actual contribution of phonons induced by radioactivity to the qubit performance is not well understood. The most likely scenario comprises two different effects:

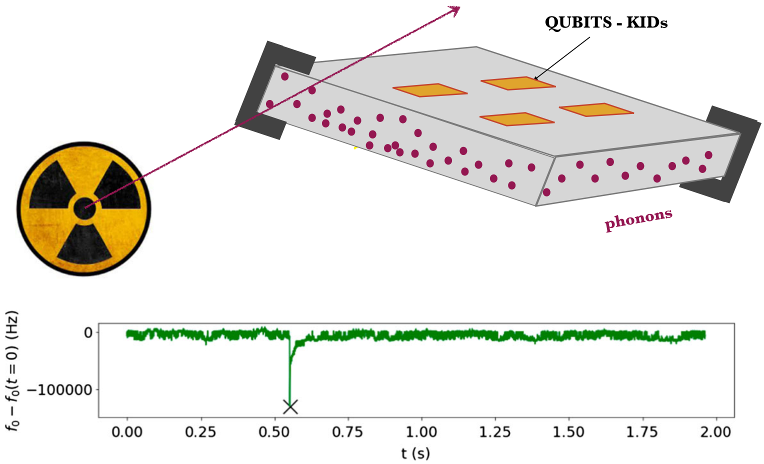

Fig. 1 *Top*: pictorial view of the expected effects of radioactivity on qubits: an interaction in the substrate produces a population of phonons. Phonons can be evacuated through the link to the thermal bath, or they can reach the qubit breaking Cooper pairs into quasiparticles. *Bottom*: typical quasiparticles burst. The plot shows the signal transmitted past a superconducting circuit operated as a kinetic inductance detector. This device can be sketched as a resonator with a resonant frequency (f_0) which depends on its inductance and capacitance. Energy deposits in the device break Cooper pairs into quasiparticles, changing the kinetic inductance. This phenomenon results in an abrupt shift of the resonant frequency toward smaller values. Then, quasiparticles start to recombine back into Cooper pairs, restoring the initial condition. Color figure online

1. The radioactive interaction results in a large quasiparticles burst. A single instantaneous energy deposit in the substrate produces a distribution of phonons that travel in the substrate and are quickly evacuated through the chip holder. During this process, a fraction of phonons can enter the qubit and break some Cooper pairs into quasiparticles, producing a burst in the quasiparticle density. The length of the burst will depend on the collection time of phonons: the sooner they are evacuated through the inert material, the shorter the rise-time of the burst. Quasiparticles will then recombine back into Cooper pairs, with a time constant that depends on the superconductor (Fig. 1, bottom), restoring the initial situation.
2. The radioactivity produces a steady population of quasiparticles (or bursts with too small amplitude to be disentangled from the fluctuations of the quasiparticles density) . A high rate of low-energy interactions (for example, an infrared radiation constantly illuminating the substrate) would produce a steady population of phonons that cannot be quickly evacuated. The phonon population, in turn, would lead to a hardly predictable non-equilibrium quasiparticles population.

The first case can be studied exploiting the distinctive signature of these events. Quasiparticles bursts can be easily identified with simple trigger algorithms and, if they are induced by the described mechanism, they should appear in time-coincidence in all the qubits deposited on the same substrate. Indeed, an energy release in the substrate generates waves of phonons which are simultaneously absorbed by all the active devices deposited on the substrate [13]. The starting point for our measurements is the work of L. Gruenhaupt et al. [14], in which the authors observed quasiparticles bursts with a rate of ∼50 mHz. The authors did not attempt to correlate these bursts with radioactivity, or to study time-coincidences among different devices, which will be the goal of our study.

We highlight that quasiparticle bursts are not worrisome for the performance of the single qubit, as long as their rate is low enough. However, they can severely impact quantum error correction, which relies on the capability of storing the information of a qubit in a highly entangled state of several qubits. Therefore, understanding (and suppressing) this kind of events is fundamental for the development of quantum processors.

The second class of events is more difficult to investigate, as it results in a general deterioration of the qubit performance which could also be related also to other phenomena. A non-equilibrium quasiparticles population can be detrimental in many ways: quasiparticles can absorb the qubit energy and dissipate it via phonons, excite the qubit, change the energy difference between the two levels and so on, impacting the coherence time of the single qubit.

Our project foresees two main steps. First, we want to demonstrate that instantaneous quasiparticle bursts are mainly caused by natural radioactivity, and that we can provide a path for their reduction. Then, we want to understand if the two classes of events are correlated, i.e., if a reduction in the number of quasiparticles bursts results in an improvement of the single qubit performance.

3 Kinetic inductance Detectors as Proxy for Qubits

To test the effects of radioactivity on the qubit performance, we plan to use kinetic inductance detectors [15,16] (KIDs) as test devices.

KIDs recently gained a lot of attention as they offer exquisite energy resolution and are naturally multiplexed in the frequency domain, enabling the realization of large arrays monitored with a few readout lines. For this reason, they are now subject of an intense R&D activity for applications in astrophysics [17–23], in X-ray spectroscopy [24,25], in the search for Dark Matter [26,27], in precision measurements of the coherent elastic neutrino-nucleus scattering [28] and in double-beta decay searches [29–33].

To a first approximation, KIDs and qubits share many technological aspects: they are both made of thin superconducting layers deposited on larger substrates and operated in dilution refrigerators with microwave circuitry. Since their hardware implementation is so similar, it is reasonable to assume that their response to radioactivity will be more or less the same. On the other hand, the operation of KIDs is much simpler than qubits and this is the first motivation to use them as test devices in our project. Another advantage is that since KIDs are developed as radiation detectors, they already offer the electronics and software tools to trigger, reconstruct and analyze quasiparticle bursts in detail.

Finally, it is worth highlighting that the KID community is now actively trying to understand the mechanism that relates radioactivity to phonons, and phonons to quasiparticle variations in the detector [34]. While KIDs developers are trying to enhance the signal-to-noise ratio of the detectors by collecting more phonons, the

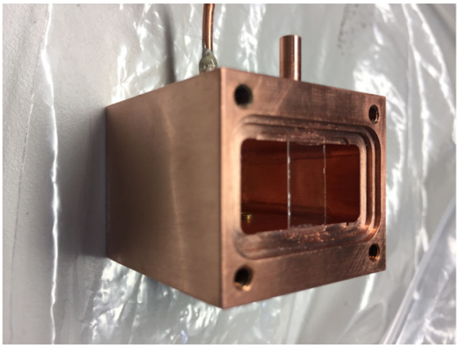

Fig. 2 First measurement prototype. A $15 \times 8 \times 0.33\,\mathrm{mm}^3$ sapphire crystal is anchored using cryogenic grease to the copper holder, acting also as waveguide. Three GrAl resonators (not visible because of the very small size) are deposited in the center of the sapphire crystal. Color figure online

qubit community is trying to suppress as much as possible the phonon population to prevent interactions in the qubit. Thus, even if the final goal is different, there is a large overlap of expertise, and progresses in these directions can benefit both the research fields.

4 Methods

As explained in the previous section, KIDs are an ideal benchmark to investigate the effects of radioactivity in qubits. For the first test, we fabricated KIDs using granular aluminum (GrAl), a promising material for qubits [35,36]. We deposited three 20-nm-thick GrAl resonators on a single $15 \times 8 \times 0.33\,\mathrm{mm}^3$ sapphire crystal. The surface of the resonators was varied in order to feature different phonon collection efficiencies ($600 \times 10\,\mu\mathrm{m}^2$, $1000 \times 40\,\mu\mathrm{m}^2$ and $420 \times 5\,\mu\mathrm{m}^2$). A picture of the prototype, assembled in a copper waveguide, is shown in Fig. 2.

The first measurement will consist in exposing this prototype to an intense γ-source, to prove that:

- The rate of quasiparticles bursts depends on the radioactivity level;
- These bursts occur in time-coincidence in the three KIDs, meaning that the interaction that produced them did not occur in a single KID but in the whole substrate.

Then, the same prototype will be used to study the different contributions of the natural radioactivity, in order to understand which of them are most worrisome for the operation of qubits. More in detail, we will study the cosmic rays, environmental radioactivity and contaminations of the materials.

Comprising mainly muons, cosmic rays can cross the device releasing energy by direct ionization. In this case, we expect an energy release ranging from tens to hundreds of keV, depending on the substrate density/thickness and on the incident angle of the muon. Nevertheless, most cosmic rays can interact in the inert material close to the detector, inducing electromagnetic showers that, in turn, can hit the substrate. To investigate the importance of this contribution, we will operate the same device in an above-ground and in a deep underground cryogenic facility. The above-ground tests will be performed using a cryostat already instrumented for qubits and KIDs operations located at the Karlsruhe Institute of Technology (Germany), while for the underground measurements we will exploit the cryogenic facility of the Laboratori Nazionali del Gran Sasso (Italy). We recently completed the commissioning of the readout line for the operation of KIDs in the underground cryostat.

Beside the cosmic rays, the environment in which the qubit is operated is contaminated by the natural occurring radioactivity, due for example to ^{232}Th, ^{238}U and their daughters, to ^{40}K (the largest source of radioactivity in animals and humans), and to Rn, a natural contaminant of the air with an activity of tens of Bq/m^3. This contribution is hard to predict as it strongly depends on the materials used for the site construction and on its ventilation. We will assess the impact of environmental radioactivity to the rate of quasiparticles bursts by measuring the same device with and without thick passive shields.

All the previous sources of radioactivity can be strongly reduced, exploiting the know-how offered by experiments searching for extremely rare events. Once the "external" sources are suppressed, contaminations of the materials that constitute the detector itself become the main issue. To mitigate this risk, all the materials must be carefully selected, cleaned and stored in order to avoid re-contaminations. We will operate the same chip using standard materials for qubits operation and then cleaner materials (i.e., materials selected for their radio-purity and further treated to remove surface contaminations).

These measurements will allow to disentangle the various sources of quasiparticles bursts and to provide a path for their reduction. We also highlight that the proposed measurements will allow to establish if qubits will have to be operated in deep underground laboratories, or if the contribution of cosmic rays can be mitigated in surface laboratories. Finally, we will investigate a possible correlation between the rate of quasiparticles bursts and the general features of the resonator (internal quality factor, sensitivity…) in order to understand if the suppression of the bursts can eventually impact the qubit performance.

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