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Simulating Alpha Particles Incident on MKID Chips for Quantum Sensitivity Analysis

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Abstract

Superconducting quantum devices, such as microwave kinetic inductance detectors (MKIDs), are highly sensitive instruments used in quantum computing and advanced sensing technologies. However, their extreme sensitivity also makes them vulnerable to background noise from natural sources like radiation. One significant contributor to this noise is alpha particles emitted by ^{210}Po, a radon decay daughter that accumulates on surfaces near the detector. This project investigates how alpha particles emitted from ^{210}Po interact with MKID chips. These particles can deposit energy on the detector surface, disrupting its operation and generating false signals. Understanding the energy and behavior of these particles is crucial for improving the design and reliability of quantum devices. To explore this, we first modeled the decay chain starting from ^{210}Pb to ^{210}Po using differential equations. This allowed us to predict how the activity of alpha-emitting isotopes changes over time, reaching a steady state after about two years. Next, we simulated alpha particle interactions with the MKID chip using the Geant4 software toolkit. We built a detailed computer model of the detector housing, including the copper lid where alpha particles originate, the silicon chip, and a thin aluminum sensor layer. Alpha particles were emitted isotropically from just beneath the copper lid's surface, mimicking natural decay conditions. The simulation tracked how these particles deposit energy on the chip, generating electron-hole pairs and phonons. The results provide insight into the behavior of the resultant electron-hole pairs and phonons, giving us a clear understanding of the energy deposition distribution on the chip. This work supports efforts to mitigate background noise in superconducting sensors, advancing their use in quantum computing and sensitive physics experiments.

1 Introduction

Superconducting quantum devices, including qubits and microwave kinetic inductance detectors (MKIDs) [3], are at the forefront of both quantum computing and next-generation sensing. Their extreme sensitivity to environmental perturbations makes them powerful tools for probing rare physics events, but also highly susceptible to unwanted interference, particularly from background radiation and cosmic rays. Understanding how these particles interact with these sensors is essential for both improving quantum computer robustness and exploring potential sensing applications such as dark matter detection.

Fermilab's Cosmic Quantum (CosmiQ) group conducts a broad range of studies to characterize radiation-induced effects on superconducting devices. A key part of this effort involves measuring how qubits and MKIDs respond to interactions with different particles — such as alphas, betas, gamma rays, and muons - using a combination of surface-level and underground laboratories. Within this broader initiative, this focused subproject examines the specific effects of alpha particle interactions on superconducting devices, with the goal of informing quantum computing hardware developers about the implications of alpha-induced noise in large-scale quantum processors. This work is intended to support a forthcoming publication addressing how naturally occurring alpha backgrounds could impact the operation of hundred thousand to million qubit scale systems.

This summer research project contributes to that goal through the simulation of alpha decays from ^{210}Pb plated onto the copper lids of MKID chip housings. As part of an experimental campaign, copper components are exposed to high levels of radon at the South Dakota School of Mines & Technology to encourage radon decay daughter accumulation. These components are then returned to Fermilab for experimental testing. In the meantime, simulations are used to predict how alpha particles emitted from these plated surfaces travel through the housing and interact with the MKID chip.

The project consists of two main components. First, the radon decay chain is modeled using with differential equations and implemented in Python to visualize the activity profiles of ^{210}Pb, ^{210}Bi, and ^{210}Po over time. Second, particle simulations are conducted in a software package known as G4CMP [2] using a self-made housing geometry and a simplified MKID geometry to analyze energy deposition patterns on the chip and its surrounding copper housing. These results will support future experimental efforts and help assess how alpha-induced signals may scale in quantum devices operating in realistic environments.

2 Modeling the Radon Decay Chain

2.1 Deriving the Bateman Equation for Modeling the ^{210}Pb Decay Chain

We model the decay chain:

$$^{210}\text{Pb} \rightarrow {}^{210}\text{Bi} \rightarrow {}^{210}\text{Po} \rightarrow {}^{206}\text{Pb (stable)},$$

wherein ^{210}Pb is the main daughter of radon left following plate-out. Defining $N_{\text{Pb}}(t)$, $N_{\text{Bi}}(t)$, and $N_{\text{Po}}(t)$ as the number of atoms of each isotope at time t, we let λ_{Pb}, λ_{Bi}, and λ_{Po} denote the decay constants for each respective isotope. The system of differential equations modeling their behavior is as follows:

$$\begin{aligned}
\frac{dN_{\text{Pb}}}{dt} &= -\lambda_{\text{Pb}} N_{\text{Pb}}(t) \\
\frac{dN_{\text{Bi}}}{dt} &= \lambda_{\text{Pb}} N_{\text{Pb}}(t) - \lambda_{\text{Bi}} N_{\text{Bi}}(t) \\
\frac{dN_{\text{Po}}}{dt} &= \lambda_{\text{Bi}} N_{\text{Bi}}(t) - \lambda_{\text{Po}} N_{\text{Po}}(t),
\end{aligned}$$

where we assume that at the deposition time t_0, only ^{210}Pb is present:

$$N_{\text{Pb}}(t_0) = N_0, \quad N_{\text{Bi}}(t_0) = 0, \quad N_{\text{Po}}(t_0) = 0.$$

Solving the System of Equations

The first equation is a simple exponential decay:

$$N_{\text{Pb}}(t) = N_0 e^{-\lambda_{\text{Pb}}(t-t_0)}.$$

Substituting this into the second equation:

$$\frac{dN_{\text{Bi}}}{dt} = \lambda_{\text{Pb}} N_0 e^{-\lambda_{\text{Pb}}(t-t_0)} - \lambda_{\text{Bi}} N_{\text{Bi}}(t).$$

Solving this, we find the following

$$N_{\text{Bi}}(t) = \frac{\lambda_{\text{Pb}} N_0}{\lambda_{\text{Bi}} - \lambda_{\text{Pb}}} \left(e^{-\lambda_{\text{Pb}}(t-t_0)} - e^{-\lambda_{\text{Bi}}(t-t_0)} \right).$$

Substituting into the third equation:

$$\frac{dN_{\text{Po}}}{dt} = \lambda_{\text{Bi}} N_{\text{Bi}}(t) - \lambda_{\text{Po}} N_{\text{Po}}(t).$$

This yields the final expression:

$$\begin{aligned}
N_{\text{Po}}(t) = N_0 \cdot \lambda_{\text{Pb}} \lambda_{\text{Bi}} \cdot \Bigg[& \frac{e^{-\lambda_{\text{Pb}}(t-t_0)}}{(\lambda_{\text{Bi}}-\lambda_{\text{Pb}})(\lambda_{\text{Po}}-\lambda_{\text{Pb}})} \\
+ & \frac{e^{-\lambda_{\text{Bi}}(t-t_0)}}{(\lambda_{\text{Pb}}-\lambda_{\text{Bi}})(\lambda_{\text{Po}}-\lambda_{\text{Bi}})} \\
+ & \frac{e^{-\lambda_{\text{Po}}(t-t_0)}}{(\lambda_{\text{Pb}}-\lambda_{\text{Po}})(\lambda_{\text{Bi}}-\lambda_{\text{Po}})} \Bigg].
\end{aligned}$$

Finally, rearranging this expression for $N_{\mathrm{Po}}(t)$ at time t_1, we can write the initial number of deposited ^{210}Pb atoms to be

$$N_{\mathrm{Pb}}(t_0) = \frac{N_{\mathrm{Po}}(t_1)}{\lambda_{\mathrm{Pb}}\lambda_{\mathrm{Bi}}}\left[\frac{e^{-\lambda_{\mathrm{Pb}}(t_1-t_0)}}{(\lambda_{\mathrm{Bi}}-\lambda_{\mathrm{Pb}})(\lambda_{\mathrm{Po}}-\lambda_{\mathrm{Pb}})} + \frac{e^{-\lambda_{\mathrm{Bi}}(t_1-t_0)}}{(\lambda_{\mathrm{Pb}}-\lambda_{\mathrm{Bi}})(\lambda_{\mathrm{Po}}-\lambda_{\mathrm{Bi}})} + \frac{e^{-\lambda_{\mathrm{Po}}(t_1-t_0)}}{(\lambda_{\mathrm{Pb}}-\lambda_{\mathrm{Po}})(\lambda_{\mathrm{Bi}}-\lambda_{\mathrm{Po}})}\right]^{-1}.$$

This direct relationship allows us to estimate the initial ^{210}Pb deposition quantity solely based on the measured number of ^{210}Po atoms at a later time t_1.

2.2 Secular Equilibrium and Numerical Simulation of Activity Rates

Because the half-life of ^{210}Pb (22.3 years) is significantly longer than that of ^{210}Bi (5.0 days) and ^{210}Po (138.4 days), the decay chain naturally evolves toward a state known as *secular equilibrium*. In this regime, the activity (i.e., decay rate) of each isotope in the chain becomes approximately equal over time:

$$A_{\mathrm{Pb}}(t) \approx A_{\mathrm{Bi}}(t) \approx A_{\mathrm{Po}}(t).$$

This occurs because the short-lived daughter isotopes (^{210}Bi and ^{210}Po) accumulate until they reach a balance: their decay rates match the production rate from their parent. Once equilibrium is established, the entire chain decays as if it were a single isotope: the long-lived ^{210}Pb.

To visualize this behavior, the activity rates were numerically simulated using Python. The Bateman equations derived earlier were used to calculate $N(t)$ for each isotope over a two-year period, and the activity rates were then computed using:

$$A_i(t) = \lambda_i N_i(t),$$

where $i \in \{\mathrm{Pb}, \mathrm{Bi}, \mathrm{Po}\}$. Figure 1 shows the result of this simulation, with initial condition $A_{\mathrm{Po}}(t_1) = 1$ hertz and $t_1 = 1$ month.

3 Geant4 Simulation Framework

Geant4 is a C++ -based toolkit for simulating the passage of particles through matter. In this project, Geant4 was used to model alpha particle interactions with a prototype MKID (Microwave Kinetic Inductance Detector) setup. The overall goal of the simulation is to visualize the resultant particles from an alpha incident on the chip. The section is organized into two components: geometry building and particle simulation incident on the geometry.

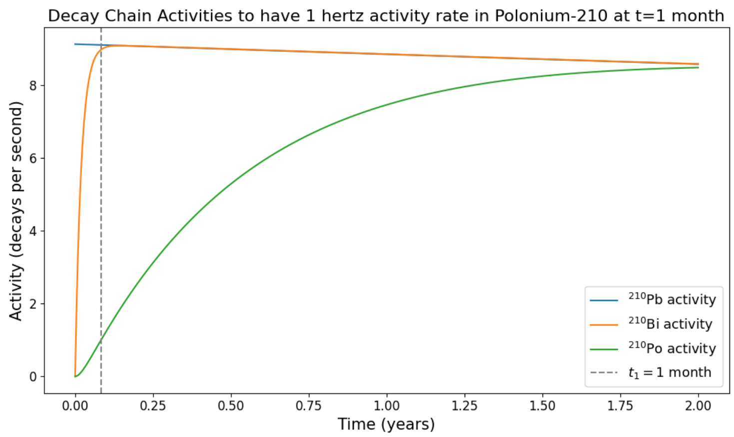

Figure 1: Activity rates of ^{210}Pb (blue), ^{210}Bi (organge), and ^{210}Po (green) as a function of time over two years. Secular equilibrium between ^{210}Pb and ^{210}Bi occurs after roughly one month (vertical dashed line), whereas secular equilibrium for the full decay chain is approached near the end of the plot after 2 years. Initial deposit of ^{210}Pb was found to be 9.26e9 atoms.

3.1 Geometry Building

To simulate alpha particle interactions in the MKID test setup, a model of the detector housing was constructed in Geant4. The geometry was built from scratch within Geant4 for control and flexibility, relying on a STL file from my team for precise dimensions. The geometry consists of a 36 mm $\times$ 36 mm $\times$ 10 mm copper box with a smaller 32 mm $\times$ 28 mm $\times$ 10 mm volume subtracted from its center to form a hollow frame. Additional internal features include a ledge and three supporting arms designed to hold the MKID chip. The MKID chip itself will be modeled as a simple 22 mm $\times$ 22 mm $\times$ 1 mm slab resting on these arms within the cavity. Material definitions in Geant4 were set to assign copper to the housing volume. A comparison of this simulated geometry with the physical chip housing is shown in Figure 2.

To prepare the model to throw alphas at the chip and housing and simulate the resulting phonons and charges, the next step involved constructing the MKID chip, sensor, and lid components. A 22 $\times$ 22 $\times$ 1 mm MKID chip made of silicon was positioned inside the housing resting directly above the arms. To enable G4CMP to simulate phonon behavior, a corresponding silicon lattice was defined and registered to the physical chip volume. A 30 nm-thick aluminum film, representing the MKID's superconducting sensor layer, was placed directly on top of the silicon with no spacing between the two. Finally, a copper lid was created as a 36 $\times$ 36 $\times$ 2.5 mm slab resting on top of the housing. This completed geometry enables later simulations in which particles will be generated from its surface and tracked through the system. This full geometry is shown in Figure 3.

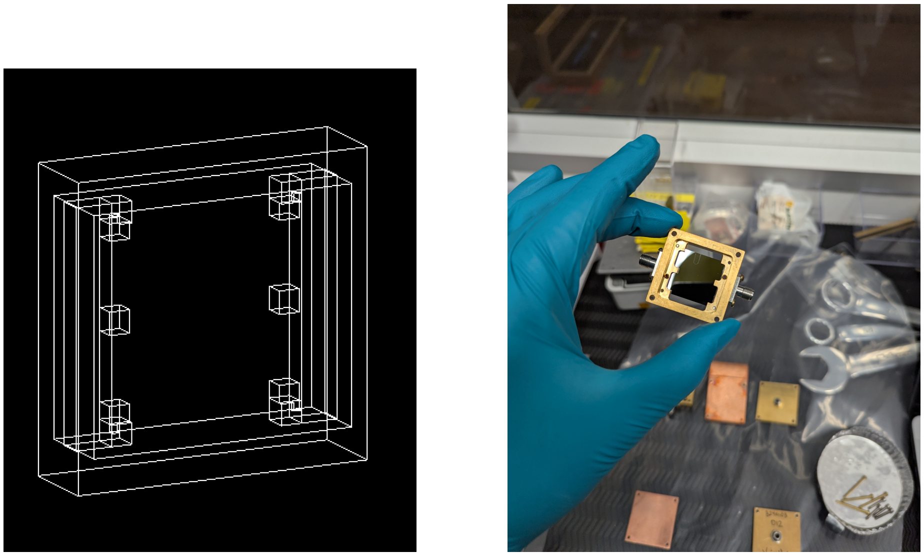

Figure 2: Comparison between the Geant4-constructed geometry (left) and the physical detector housing (right).

4 Simulations

4.1 Setup

To model particle interactions within the detector assembly, we used a Geant4 simulation enhanced with the G4CMP extension. The copper lid of the housing, defined as a G4Para volume - which is in basic terms a rectangular prism for particle generation - with dimensions 36×36×2.5mm, served as the source for particle generation. Alpha particles were emitted isotropically from a depth of 10nm in the interior-facing surface of the lid at random positions. This depth-based approach introduces alpha dependent energy loss: each alpha particle exits the copper at a different angle, resulting in varying path lengths and thus different energy losses.

To manage computational load, it was necessary to implement downsampling within the G4CMP simulation [1]. Because G4CMP models every individual resultant charge and phonon generated during alpha interactions, the number of simulated quanta can grow extremely large, often reaching millions per event. This level of granularity, while physically accurate, quickly becomes computationally infeasible given resource constraints. To address this, the simulation was configured to downsample the total number of phonons and charges recorded to 0.1% of the actual quantity generated. This approach preserves the statistical structure of the data while significantly reducing simulation time and memory usage, enabling large-scale event generation within practical computing limits.

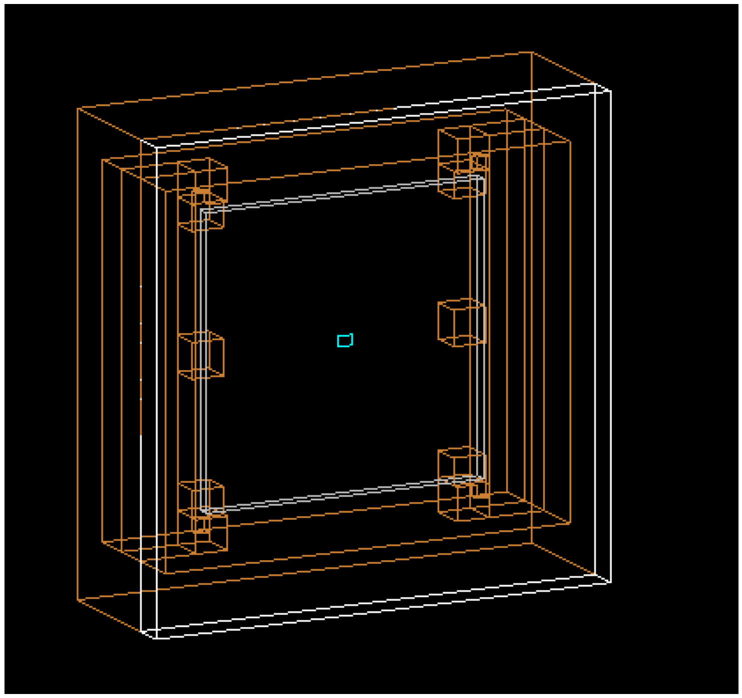

Figure 3: Updated geometry including the light grey silicon MKID chip, the 30 nm thick, cyan aluminum film on top, and a white housing lid to throw particles from.

This configuration allows a detailed study of energy deposition profiles and phonon/charge signal generation within the chip and sensor film. Results from these simulations will be discussed in the following section.

4.2 Simulation Runs

When an alpha particle emitted from the housing lid interacts with the MKID chip surface, it deposits energy. This deposited energy disrupts the superconducting state of the chip by breaking apart Cooper pairs, the bound electron pairs responsible for superconductivity. The breaking of these Cooper pairs generates free electrons and holes, which contribute to measurable changes in the chip's electrical response. This process is clearly illustrated in the electron-hole pair simulation, which shows the spatial distribution of these charge carriers immediately following an alpha interaction.

In addition to these pairs, phonons - quantized vibrations of the crystal lattice - are produced as a result of the energy deposition. These phonons play a crucial role in transferring energy within the chip and contribute to signal generation. The phonon-only simulation captures the propagation patterns of these vibrations. It is important to note that phonon behavior is highly sensitive

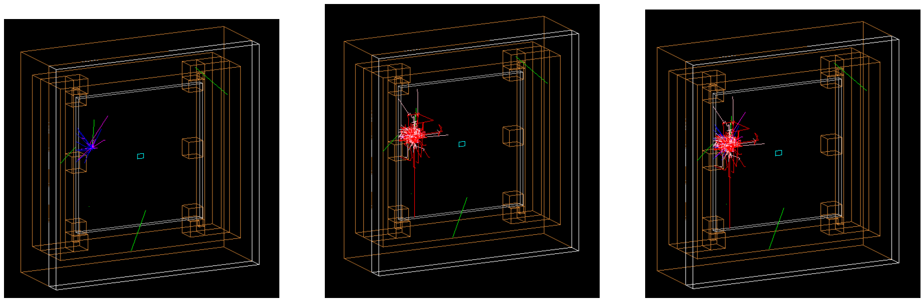

Figure 4: Visualizations of particle interactions in the MKID chip following alpha particle energy deposition. Specifically showing electron-hole pair distribution (left), phonon propagation (middle), and a combined plot of the two (right).

to boundary conditions, which are not well defined or experimentally constrained here and might affect the visualization.

To better understand combined effects, we also ran simulations including both electron-hole pairs and phonons simultaneously. The resulting visualization presents a comprehensive picture of how these electron-hole pairs and phonons coexist and interact within the MKID chip after an alpha particle event. The final simulation ran was a 1000 event simulation tracking only the alpha particles, with no resultant electron-hole pairs or phonons, to gain insight into the energy deposition distribution of the alphas. Visualizations of each of the above three cases are shown in Figure 4.

5 Results and Analysis

The simulations provided detailed insights into the behavior of energy deposition and particle interactions within the MKID chip following alpha particle impact. By modeling the energy loss of alpha particles emitted from 10 nm beneath the copper lid surface, and tracking their subsequent interaction with the silicon substrate and aluminum sensor layer, we obtained quantitative and qualitative insights into electron-hole pair and phonon dynamics.

Alpha particles that reached the chip surface had a range of energies, leading to a non-uniform deposition profile. This variation in energy deposition is critical to understanding because it directly influences the magnitude and characteristics of the signals generated within the MKID. Non-uniform energy deposition can contribute to complex noise patterns and signal variability, affecting its accuracy and sensitivity. This was modeled in the final simulation. The precision of the energy was not enough to characterize the energy loss with a fitted distribution, but the energy loss, regardless of how steep or shallow the emission angle from the copper was - and therefore how far the alpha traveled

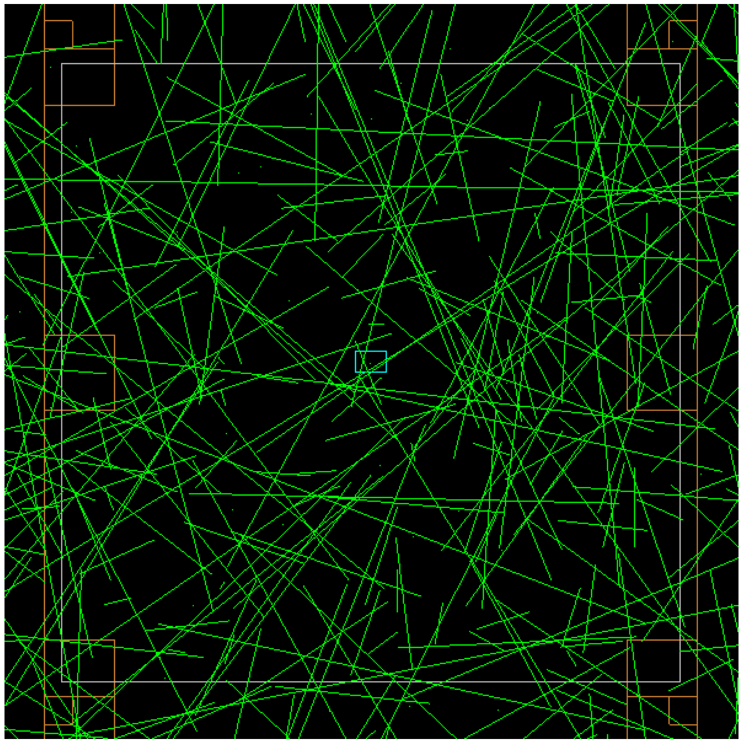

Figure 5: Visualization of the tracks of 1000 alphas emitted isotropically from the lid of the chip housing.

through the surface before exiting - was always between 0-10 keV. This means each alpha deposited 5290-5300 keV, with 5300 keV being the initial energy the alpha carried. Out of the 1000 particles generated and thrown, 152 of them reached the chip, about 15%. A projected visualization of these tracks is shown in Figure 5.

Acknowledgements

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