PROCEEDINGS OF SCIENCE

Dark matter detection with superconducting qubit in RADES experiment

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In dark matter detection especially for ultra light dark matter such as axion or axion-like particles, the output signals are easily buried in noise, making it challenging to reach the expected sensitivity. Recently, various detection concepts incorporating quantum technology are being explored to overcome this limitation. One of the most exciting one is with superconducting qubits as a single photon counter. In this talk we will discuss the ongoing work to develop quantum sensing with superconducting qubit in the RADES experiment.

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1. RADES experiment

In the RADES experiment, we use a haloscope setup [1], basically utilizing a single cell or multi-cell RF cavity, searching for the relic dark matter axions. A previous setup was installed in the magnet bore of the CAST experiment [2, 3], the result has been published [4]. Another data-taking result at CERN SM18 magnet has been released recently and is currently under review for publication [5]. In addition, the collaboration prepares a lower frequency scan (around 200 – 500 MHz) [6]. It would be a fully scaled setup that installed in the magnet bore of the babyIAXO solar axion telescope [7, 8]. New cavities and a tuning technique are being developing.

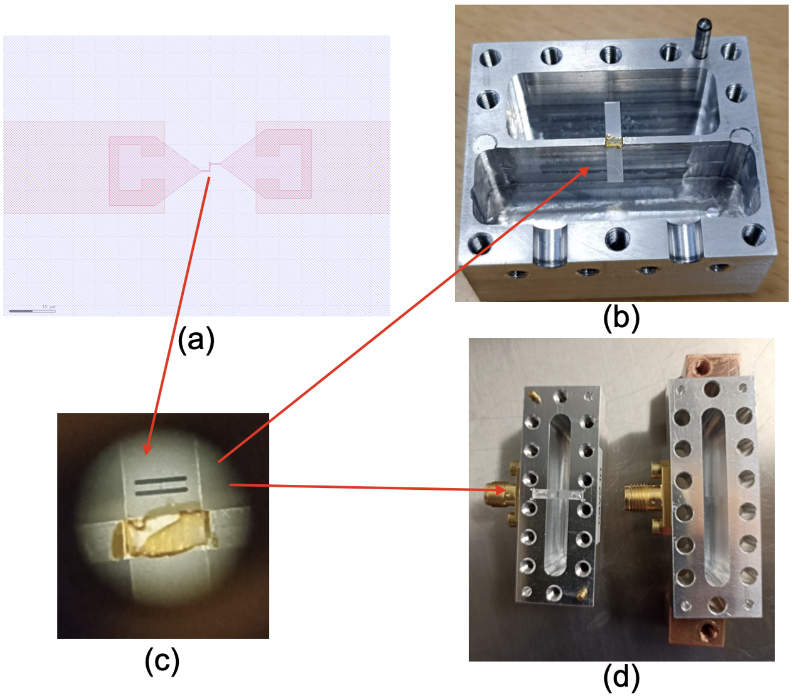

Figure 1: Qubit design and test with different cavities for RADES experiment. a) Design of the josephson junction for the transmon. b) The double cavity setup with transmon in between. c) Transmon shown in the microscope. d) A tested single cavity with transmon.

2. Quantum sensing in RADES

For ultra light dark matter detection, extremely weak signals from axion-photon conversion are expected after pre-amplification from the RF cavity in the cryostats. Currently, in most of the best experiments and designs, the output signals came from linear amplification, and which is limited by the standard quantum limit (SQL) [9]. It is a fundamental noise limit due to the quantum fluctuation. This unavoidable quantum noise arise from linear amplifcation which can be parameterised as a noise temperature, $T_{\text{SQL}} = h\nu/k_B$, where h is Planck's constant, ν is the frequency of the signal and k_B is Boltzmann's constant. For single-photon counter, on the other hand, do not suffer from the same quantum noise limitations as linear amplifiers. It is only sensitive to the number of photons. One of the noise sourses for single-photon counter would be the thermal noise from the detection of thermal photons. However, at very low temperatures (e.g., 10 mK), the number of thermal photons becomes extremely small, so the noise from thermal photons can be negligible. Single-photon counters are primarily limited by shot noise, which arises from the statistical fluctuations in the number of detected photons. At low temperatures, the shot noise from thermal photons is much smaller than the quantum noise introduced by linear amplifiers. Therefore, single-photon counters offer a significant advantage over linear amplification, as they are not constrained by the standard quantum limit (SQL). By directly detecting individual photons, they achieve much higher sensitivity, especially at low temperatures where thermal noise is minimal.

With the development of the quantum technology, interesting ideas and designs have been applied in dark matter or axion detection. Using superconducting qubit as a single photon counter is one of the most promising ideas [10]. As a single-photon counter, the qubit-cavity system functions as a two-level system. By analyzing the readout, the qubit's state can be determined. This, in turn, provides information about the number of photons present in the cavity. In this approach, similar as state squeezing, one quadrature of uncertainty is reduced while the other one is increased. The phase information of the photon will be ignored and only the amplitude or the number of photon is measured. In the dark matter detection, we focus more on the probability whether there is some ultra light particle that converted into photon. Most of the time, the phase information can be neglected. In this case, qubit becomes a perfect single photon detector.

3. Design and measurements with Superconducting qubit

The qubit and cavities system can be described by the Hamiltonian:

$$\mathcal{H} = \omega_c a^\dagger a + \frac{1}{2}\omega_q \sigma_z + 2\chi a^\dagger a \frac{1}{2}\sigma_z, \tag{1}$$

where the first term shows the cavity state with the transition frequency of the cavity ω_c and photon number operator $a^\dagger a$, the second term indicates the qubit state with qubit frequency ω_q and state operator σ_z, the last term is the interaction between the cavities and qubit where χ shows the frequency shift with different photon number in the cavity.

The design of the setup is a combination of two cavities as shown in Fig.1b, the cavity with ports connections is called readout cavity and the other one is often named storage cavity. The two cavities are connected via a superconducting transmon. The basic idea is that when the setup is installed under a strong magnetic field, axion can be converted to photon in the storage cavity via Primakoff process. Once the photon number in the storage cavity changes (e.g. from 0 to 1), the state of the qubit will change. Afterward from the readout cavity, the qubit state can be determined from the transition frequencies. The qubit used in RADES is a transmon [11] made with a Josephson junction as shown in Fig.1a. Several test cavities have been measured to estimate the performance of the qubits comparing with the simulation [12].

The dark count rate or the cavity photon occupation probability can reach 7.3×10^{-4} with similar setups in the literature [10]. We expect a similar level and even lower rate with the help of the underground lab facilities at LSC Canfranc.

With the support of DarkQuantum project (ERC-SyG), RADES is aiming to scan two unexplored mass ranges of axion and reach the QCD axion band. One is the low frequency part (around

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200 – 500 MHz) as mentioned before to take advantage of the big magnet bore of babyIAXO. The other mass range is from lower than 5 GHz to up to 18 GHz as a high frequency part. In which the superconducting qubits will play a crucial role in enhancing sensitivity.

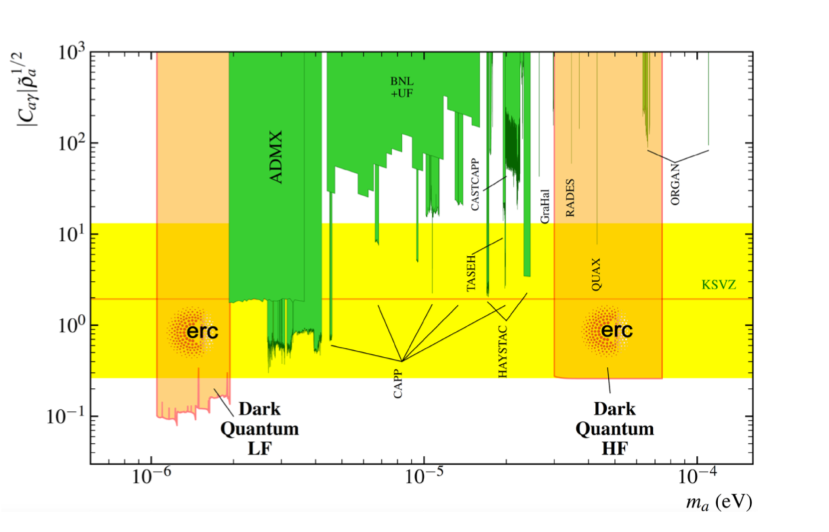

Figure 2: Targeted range of axion mass for the RADES experiment within the DarkQuantum Project.

4. Conclusions

Quantum technology is being developed in the RADES experiment. The new sensor, designed as a single-photon detector, will significantly improve the sensitivity for detecting dark matter axions. Fig.2 shows the targeted axion mass range for the RADES experiment in the DarkQuantum project. New cavities are being designed together with the new batch of transmons, see Fig.3.

(a) (b)

Figure 3: One of the dedicated cavities with a batch of newly-designed qubits.

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