

Enhancing axion searches with quantum coincidence in superconducting qubits(*)

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Summary. — This work focuses on the proposal of a quantum non demolition detection scheme with the aim of enhancing the sensitivity of the axion dark matter signal. The proposed detection scheme consists of two qubits coupled to the same three-dimensional (3D) storage cavity as well as to their own readout resonators. Quantum dynamics and electromagnetic simulations are performed to analyze and characterize the qubits and cavities, providing insights for fabrication.

1. – Introduction

One of the most remarkable discoveries of modern cosmology is that a significant fraction of the universe is composed of dark matter. The enigmatic nature of dark matter has prompted physicists to explore candidates beyond the Standard Model. Among these, the axion, a hypothetical new pseudoscalar particle introduced by Peccei and Quinn to solve the strong CP problem in quantum chromodynamics (QCD), is a prime

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candidate for dark matter [1]. Axions can be converted to microwave photons in a strong magnetic field via the inverse Primakoff effect [2]. The quest for axions as dark matter encompasses a variety of distinct experimental approaches. One the most used is the haloscope, a detection method pioneered by P. Sikivie [3], which employs a high-quality-factor (high-Q) resonant cavity immersed in a strong magnetic field. This kind of detection scheme has been employed by a large number of axion-search experiments, including the INFN-funded QUAX experiment [4]. In this configuration, the signal is amplified using a low noise electronics connected to the high-Q cavity. The power generated by the axions conversion is given by (for $\omega_{axion} = \omega_{cavity}$ and $\hbar = c = 1$) [3, 5]:

$$(1) \quad P \propto \left(\frac{g_{a\gamma\gamma}^2}{m_a^2} \rho_a\right) \left(\frac{\beta}{1+\beta} \omega_c \frac{1}{\mu_0} B^2 V C Q_L\right)$$

where $B, V, Q_L, C, g_{a\gamma\gamma}, m_a, \rho_a, \omega_c, \beta$ are respectively the magnetic field, the volume of the cavity, its loaded quality factor, the form factor, the axion-photon coupling, the axion mass, the local density of dark matter the cavity resonance frequency and the cavity coupling. The power P necessary to reach the sensitivity of the KSVZ theoretical benchmark is $\sim 10^{-24}W$ (for axion frequency of 10 GHz), which means that the most sensitive instruments are necessary. As a consequence, haloscope experiments faces limitations in scan speed and sensitivity as very high-Q cavities are needed to increase the conversion signal.

The latest breakthroughs in quantum sensing paved the way for advancements in axion searches. The advent of single microwave photon counters based on superconducting qubits has the potential to enhance the sensitivity to elusive particles like axions. This enhancement is attributed to the ability of the qubits to detect single microwave photons using quantum non-demolition (QND) protocols that allow to measure the same photons multiple times. In this work we studied the performances of a QND itinerant photon detection scheme based on two qubits. In comparison to the one qubit case described in [6], our protocols searches for events when both the qubits are in the excited state as a fingerprint of the photon presence. Looking for two qubits coincidence events will reduce the dark counts down to the thermal limit.

2. – System Model Description

We adopted a QND approach, that was first introduced in [7, 8], to devise the single microwave photon counter. Unlike conventional detectors that absorb and destroy photons, in a QND measurement, the detector interacts with the photon field preserving its quantum state, thus allowing the same photon number state to be measured multiple times. A QND itinerant single-photon counter based on one qubit was presented in [6]. We extend this approach to a two qubit device. Our approach involves two independent qubits, which are dispersively coupled to a single storage resonator and to their own readout resonators. In this configuration, the incoming microwave photon interacts with the qubits in the storage cavity (see fig. 1). The interaction between the qubits and the storage cavity is described by the Jaynes-Cummings Hamiltonian in the dispersive regime:

$$(2) \quad H = [\omega_r + \chi_1 \sigma_1^z + \chi_2 \sigma_2^z] a^\dagger a + \sum_{i=1}^2 \frac{\omega_i}{2} \sigma_i^z$$

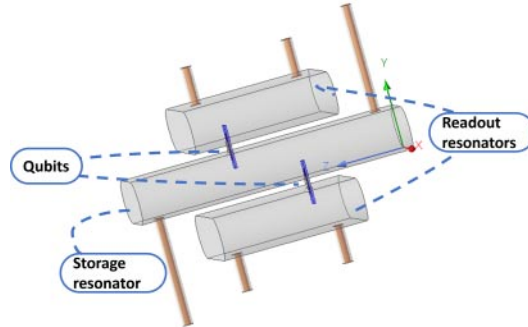


Fig. 1. – Design of 3D double-qubit single-photon detector. Ansys HFSS is used for the layout of the design.

where ω_r is the frequency of the cavity, ω_i is the frequency of the i -th qubit (with $\omega_1 \neq \omega_2$), χ_i is the dispersive shift of the i -th qubit and σ_i^z the Pauli matrix. The dressed resonator frequency is qubit-state dependent and so are its reflection properties. In other words, the way a photon is reflected by the resonator depends on the qubits state $|\psi(t)\rangle$. The QND protocol consists of a Ramsey measurement started by preparing each qubit in the state $|+\rangle = \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)$. When a photon with frequency ω_r impinges on the storage cavity each $|+\rangle$ state evolves into $|-\rangle = \frac{1}{\sqrt{2}}(|0\rangle - |1\rangle)$ if $\chi_1 = \chi_2 = \chi$ and $2\chi \gg \Gamma$, where Γ is the cavity linewidth. Completing the Ramsey cycle with a $-\pi/2$ pulse the qubits are rotated in the state $|11\rangle$ in case of photon presence or in the state $|00\rangle$ otherwise (see fig. 2) [9].

The probability $P(1|0)$ to measure the qubit in the state 1 when the qubit is in 0 is typically 0.5%. For a single qubit detector, the rate of dark counts is proportional to this probability, while for a two qubit detector, this rate is proportional to $P(1|0)^2$ with a reduction of about two orders of magnitude of the dark count rate.

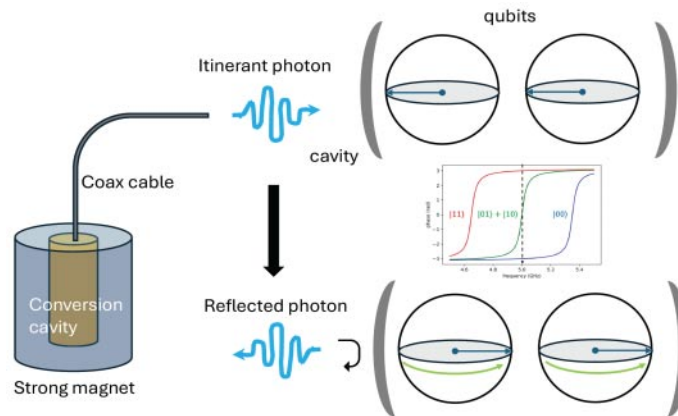


Fig. 2. – Sketch of the detection of an itinerant photon with the two qubit device.

3. – Simulations

To study the performance of the two qubit detector we simulated its quantum state dynamics and then analyzed the system time evolution using QuTiP [11]. We use the input-output formalism described in [12] considering the system Hamiltonian shown in eq. (2).

We first compute the quantum efficiency of our detector. This provides insights into the optimization of the system parameters to achieve near-unity detection efficiency for the final state $|11\rangle$. The quantum efficiency is computed as the probability $p_{ee} = |\langle ee|\psi(t = t_f)\rangle|^2/|\alpha_{ch}|^2$ of having the qubits in the excited state at the final time t_f , where α_{ch} is the amplitude of the weak coherent state ($|\alpha_{ch}|^2 \ll 1$). In fig. 3 (left) we show the evolution of the quantum state of the two qubits in presence of a coherent pulse ($\chi_1 = \chi_2$). We considered an intrinsic quality factor of the cavity $Q_I \sim 3.7 \times 10^6$, an external width $\gamma_{ex}/2\pi = 275$ kHz and a resonance frequency of ~ 8.83 GHz corresponding to the frequency of the axion signal expected in the haloscope of the QUAX@LNF experiment [4]. We also show in fig. 3 (right) the efficiency in the case $\chi_1 \neq \chi_2$. To achieve a detection efficiency of above ~ 0.9 the difference between χ_1 and χ_2 must be less than about $2\pi \times 30$ kHz.

Ansys HFSS [13] and PyEPR [14] analysis were used to simulate the electromagnetic response of the device and to determine the coupling strengths ($g_{01}^{r,s}$) of the readout-qubit and storage-qubit, the dispersive shifts as well as the qubits anharmonicities (α). The results are summarized in table I. The electromagnetic simulation show that $\chi_1 - \chi_2 = 2\pi \times 40$ kHz, pointing out that for two transmons with the same geometry but different critical current, the electromagnetic design of our system is compatible with a small difference in dispersive shifts.

We begun the fabrication and characterization of Al transmon to employ them in the two qubit detectors. We investigated a transmon qubit, fabricated in Rome at CNR-IFN, placed within a cavity made from pure aluminum (5N) fabricated at the National Laboratory of INFN in Legnaro (Padua).

We performed two tones spectroscopy to measure the qubit absorption spectrum (see fig. 4 left panel), observing the transition frequencies up to the third-excited state.

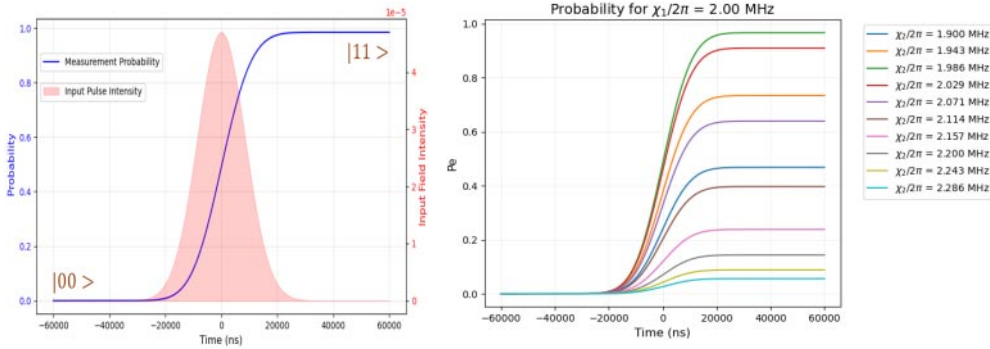


Fig. 3. – Time evolution of the efficiency computed as the probability $P_{ee}/|\alpha_{ch}|^2$. (Left) Efficiency as a function of time in presence of a gaussian coherent signal of amplitude α_{ch} . (Right) Efficiency as a function of time for different values of the dispersive shift considering $\chi_1 \neq \chi_2$.

TABLE I. – *Simulated readout-qubit-storage parameters.*

Parameters	QB1	QB2
$f/(2\pi)$ [MHz]	4279.35	4101.41
$\alpha/(2\pi)$ [MHz]	73.28	80.86
$g_{01}^{r-q}/(2\pi)$ [MHz]	81.13	81.84
$g_{01}^{s-q}/(2\pi)$ [MHz]	100.91	103.72
$\chi_{r-q}/(2\pi)$ [MHz]	2.01	1.88
$\chi_{s-q}/(2\pi)$ [MHz]	2.46	2.50

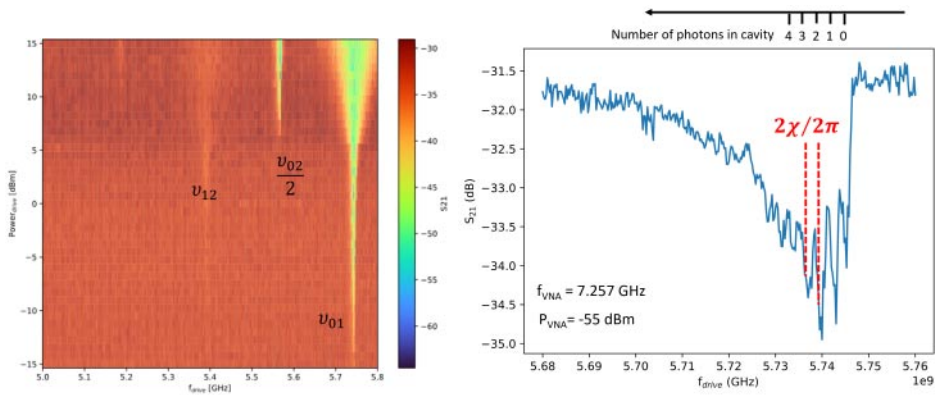


Fig. 4. – Qubit spectroscopy. (Left) The readout signal transmission S_{21} was registered for different drive frequencies and power. (Right) Qubit spectroscopy revealing the photon number occupation in the cavity measured with a VNA.

We also resolved individual Fock states inside the cavity [15] as reported in fig. 4. We measured a value of $\chi/2\pi = -1.2$ MHz and a coupling to the cavity $g/2\pi \approx 90$ MHz.

4. – Conclusion

In this study, we propose a design for a detector of itinerant single photons based on two superconducting qubits coupled to a microwave cavity with the purpose of enhancing the sensitivity of axion detection experiments. The quantum simulation of the qubits-cavity system shows that we can reach high efficiency of photon detection using appropriate values for the dispersive shifts and the cavity width. We show with electromagnetic simulations that these values are achievable, and fabricated and measured an Al transmon qubit with good values of dispersive shift. This work is a first step toward the fabrication of a two qubits QND photon counter that hold large potential to enhance axion-dark matter search.

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