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Detecting Axion Dark Matter with Superconducting Qubits

Akash Dixit, Aaron Chou, and David Schuster

Abstract Axion dark matter haloscopes aim to detect dark matter axions converting to single photons in resonant cavities bathed in a uniform magnetic field. A qubit (two level system) operating as a single microwave photon detector is a viable readout system for such detectors and may offer advantages over the quantum limited amplifiers currently used. When weakly coupled to the detection cavity, the qubit transition frequency is shifted by an amount proportional to the cavity photon number. Through spectroscopy of the qubit, the frequency shift is measured and the cavity occupation number is extracted. At low enough temperatures, this would allow sensitivities exceeding that of the standard quantum limit.

1 Single Photon Readout

In a haloscope seach for axions, the signal signature is a population of a cavity mode with resonant frequency equal to axion mass and electric field with spatial overlap with the external magnetic field. Readout of this signal is enabled by quantum limited amplifiers which measure the power stored in the microwave cavity. The quantum limit manifests itself as zero point fluctuations of the resonator modes setting an irreducible noise floor. Searches for higher mass axions ($\geq 10GHz$) require smaller wavelength cavities whose volume shrinks as λ^3 resulting in a lower signal rate. Additionally, the noise rate associated with zero point fluctuations scales linearly with frequency (ω). The signal to noise ratio drops rapidly such that the scan rate be-

Akash Dixit, Department of Physics
University of Chicago e-mail: avdixit@uchicago.edu

Aaron Chou
Fermilab

David Schuster
University of Chicago

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comes untenable. To increase the signal the target volume can be increased possibly by power combining multiple smaller cavities or increasing the external magnetic field. Each of these presents significant challenges in complexity and cost. The other possibility is to implement a readout scheme that is insensitive to the noise floor by measuring only a single quadrature of the cavity field. Rather than measuring power stored in the cavity mode, counting the photon population provides the information about the axion mass without incurring the uncertainty added by a linear amplifier operating at the quantum limit [1] [2]. In accordance with the Heisenberg uncertainty principle, the back action from this noiseless amplitude measurement results in the randomization of the photon phase. However, the phase provides no information about the mass of the axion and increased fluctuations in this quadrature do not degrade the measurement.

2 Cavity Quantum Electrodynamics

A single photon measurement can be made using the interaction between the resonator and a qubit (two level system). The physics of this interaction is governed by the Jaynes-Cummings Hamiltonian. In second order perturbation theory with qubit-cavity coupling (g) much smaller than both the cavity (ω_c), qubit(ω_q) transitions the Hamiltonian is given by:

$$\mathscr{H} = \omega_c a^\dagger a + \omega_q \sigma_z + \frac{g^2}{\Delta} a^\dagger a \sigma_z \tag{1}$$

Δ is the difference in the cavity an qubit frequencies. The interaction term contains only number operators and thus commutes with the unperturbed Hamiltonian. This allows us to perform quantum non demolition measurements of the cavity photon number (or qubit population). This effect manifests itself as a frequency shift of the qubit (cavity) transition as a function of cavity photon (qubit) population.

3 Microwave Cavity

A standard cavity, compatible with e solenoid magnet, at $\sim 10GHz$ would employ the TM010-like mode of a right cylindrical cavity (r=12mm). For integration with a superconducting qubit, the geometry must be modified such that the sensor is contained in a region free of magnetic flux. This is achieved by aperture coupling another long right cylindircal cavity with slightly larger radius (r=12.1mm) to the standard cavity. The lowest order mode (9.52 GHz) of this composite system can be approximated as the TM010 of the larger radius cavity which has minimal coupling to axion induced field but maximal coupling to the qubit making it ideal to **readout** the quibt state. The next mode (9.65 GHz) has nonzero coupling to both the axion field and qubit and will serve as the **detection** mode.

4 Transmon Qubit Fabrication

Qubit frequency and coupling to cavity modes can be engineered through simulation with HFSS and the blackbox calculator [3]. Qubit fabrication is a multistep process done either on a Silicon or Sapphire substrate. Optical lithography of a layer of Niobium produces the pads that set the charging energy, E_C, and the coupling to the cavity. Electron beam lithography is used to pattern channels for the Josephson junction. Finally, two layers of aluminum are deposited in an angled evaporator with an oxidation step in between to create the tunnel junction (AlOx) approximately 1nm in thickness (See Figure 1). The junction area and oxide thickness set the Josephson energy, E_J [4] [5]. Designing the cooper pair box to have $\frac{E_J}{E_C} \sim 100$ provides stability from charge noise and is termed a transmon qubit [6].

5 Experimental Setup

The qubit is mounted into the cavity by placing the chip into a slot through the cap. The chip contacts the copper of the cavity on one side and is held in the slot with GE varnish applied to the other side of the chip (See Figure 2). The cavity + qubit system is placed in a μ-metal shield and bolted to the dilution refrigerator operating at 20mK. The input to the cavity contains multiple attenuators including an eccosorb filter to cutoff high frequency radiation. Finally a direction coupler connects to the single antenna into the cavity which interacts with both the readout and detection mode as well as the qubit. The reflection from the antenna passes through the directional coupler into two circulators and amplified by a Low Noise factory amplifier at 4K. Measurements at room temperature are done with network

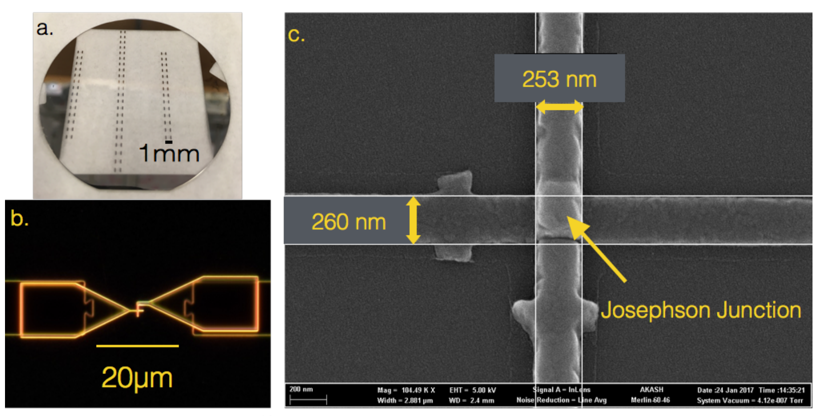

Fig. 1 a. Wafer of optically patterned capacitor pads b. Electron beam lithography c. SEM image of double angle evaporated Aluminum forming Josepshon Junction

analyzer (CW) or a homodyne setup (Pulsed) including RF sources and an arbitrary wave form generator.

6 Results

The interaction between qubit and cavity modes results in nonlinear behavior or the cavity modes which can be probed by varying the probe power and observing the resonator frequency shift (Figure 3). Driving the qubit with a pulse and allowing the excited state population decay provides a measure of the qubit lifetime (T1 $1\mu s$) (Figure 4). Varying the pulse length results in the qubit population Rabi flopping (see Figure 5). The current T1 seem to be limited by the strong coupling to the cavity modes resulting is larger loss rates. This hypothesis is currently being tested by implementing the qubit system in a cavity configuration with lower mode density (less modes to couple to) and smaller dipole arm (less coupling to modes). Additionally the excited state of the qubit has a non zero residual population which would result in a false positive signal in our scheme. Attempts to mitigate this excited state population include a clamping mechanism to well thermalize the qubit and applying magnetic flux to the capacitor pads to trap potentially excited quasi particles in the Niobium.

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Fig. 2 a. Microwave cavity b. Qubit on sapphire substrate c. Qubit chip loaded into cavity cap d. Qubit-cavity system mounted onto copper plate

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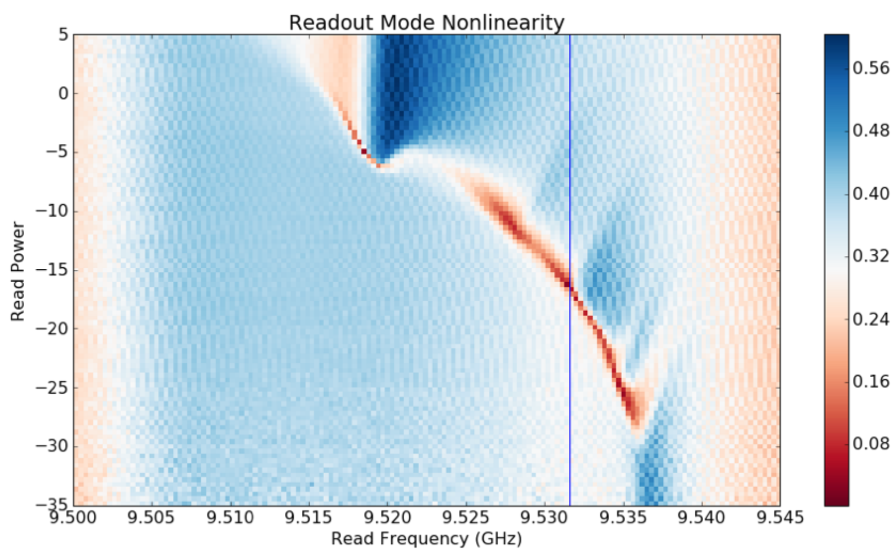

Fig. 3 This scan shows the cavity spectrum as a function of probe power (y-axis in dB). The color scale indicates the depth of the cavity resonance as measured at the digitizer. The resonator coupled to the qubit exhibits a characteristic Jaynes-Cummings nonlinearity. Increasing the probe power produces a duffing type response until the cavity frequency snaps at high photon number.

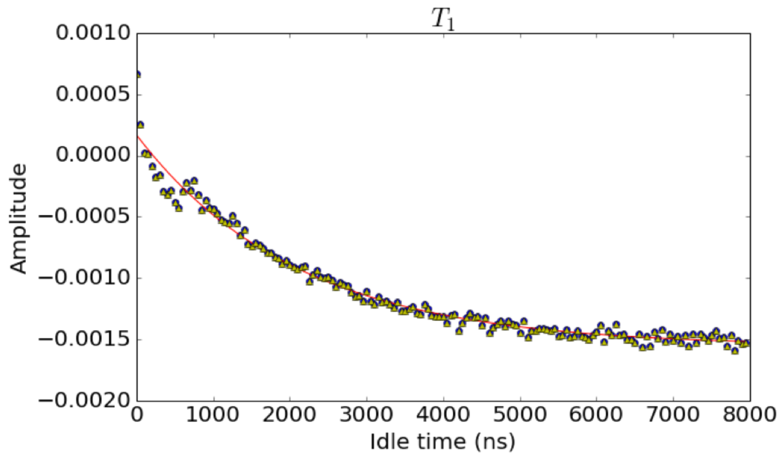

Fig. 4 Qubit population is measured at various delay times to extract the characteristic T1 decay time.

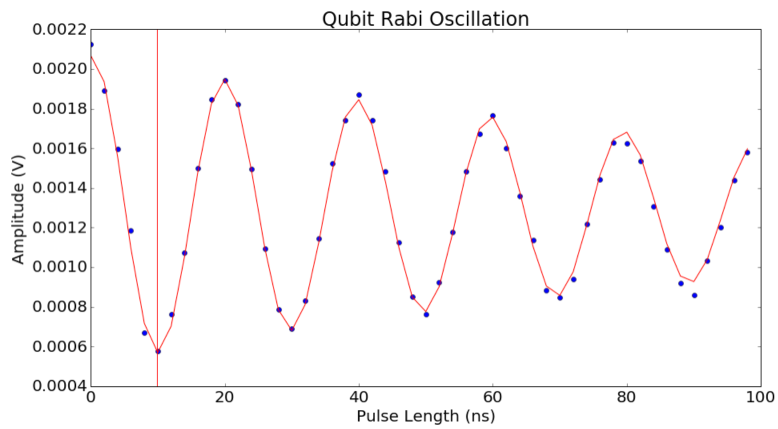

Fig. 5 Rabi oscillations between ground and excited quibt states are stimulated by driving at the qubit frequency. The qubit population is observed as it traverses the Bloch sphere. The vertical line at 10ns indicates where the qubit has reached the excited state.