Searches for wavelike dark matter utilizing superconducting qubits

Oct 16, 2024 The University of Tokyo, ICEPP Tatsumi Nitta for DarQ experiment

Axion Hunting So Far

DFSZ sensitivity

- ADMX
- CAPP

 \rightarrow Probability of discovery is too low, so far Big money (huge magnet etc) "partially" solves problems

We are investigating possibilities of superconducting qubits

New ideas and technologies are necessary for discovery

㾎Large EDM $\rightarrow 10^6 \times$ atoms

㾎Fast Readout -> *O*(10) *ns*

㾎Low Noise -> mK & shield

$0.1 \, \text{nm}$ 100 μ m

㾎Long Lifetime -> *O*(100) *μs*

*N*electron < *O*(100) Many copper pairs behaves coherently

Qubit is a giant artificial atom

Basic Properties Superconducting Qubits

As Quantum Computer …

excited state population requires a Q **uldit is so tast** Qubit is so fast

Figure 5.5: Qubit residual state population. Left. Pulse sequence for measuring qubit -> mK & shield with U.C. are green dots and with α are blue dots and without α 㾎Low Noise

Driving $|0\rangle \rightarrow |1\rangle$ takes only 10 ns

㾎Large EDM $\rightarrow 10^6$ x atoms 㾎Fast Readout -> *O*(10) *ns*

㾎Long Lifetime -> *O*(100) *μs*

Basic Properties Superconducting Qubits

As Quantum Computer …

Relatively long coherence time \mathcal{A} The energy spectrum of a quantum harmonic oscillator (\mathcal{A}). (b) The energy spectrum of the transmonal \mathcal{A}

 (10) <u>ا</u> 4 $\rightarrow 10^6$ x atoms 3 \checkmark v Fast Readout \overline{a} 㾎Large EDM -> *O*(10) *ns*

 $\mathbf I$ \checkmark 㾎Long Lifetime -> $O(100)$ μs

-π -π/2 0 π/2 π ow Noise 㾎Low Noise -> mK & shield

5 quantum harmonic oscillator **a c** As Quantum Computer …

Basic Properties Superconducting Qubits

@100 Hz帯域 ~ 10^{-19} W

If you are and α and the transmission is in ultral low noise environment

 $\rightarrow 10^6 \times$ atoms 㾎Large EDM 㾎Fast Readout -> *O*(10) *ns O*(100) *μs*

Al Basic Properties Superconducting Qubits

Here, **a**in*(t)* and **a**out*(t)* represent, respectively, the incom-㾎Low Noise interacts with our circuit. The fields at different times are -> mK & shield

As Quantum Computer …

- 㾎Strong coupling to signals
- 㾎Low readout error
- 㾎Easier operation
- 㾎Don't miss tiny signals

㾎Large EDM $\rightarrow 10^6 \times$ atoms 㾎Fast Readout -> 㾎Long Lifetime -> *O*(10) *ns* $O(100)$ μs

Basic Properties Superconducting Qubits

As Quantum Computer … As Quantum Sensor …

㾎Low Noise -> mK & shield

-
-
-

TE101 mode simulation

Qubits for quantum computing

Qubits are utilized for DM searches

counting

Storage

20an

Single photon Cavity tuning by Direct excitation Lamb shift

IIgnest sensitivity. Bor easier scan Fighest sensitivity coupled to the storage cavity. Highest sensitivity

Easier scanning

Aaron et.al. a PRL 126 141302 (2021) $\overline{}$ **Readout** Transmon | Ø | Dark Matter

reveals that the storage cavity population is imprinted as a Eor easier scanning used to provide the state of the state of an interest of the state of the state of the state of the state of t For easier scanning

Easier scanning

ulation on the qubit state by performing a cavity num-resolution on the qubit state by p

Moroi+ PRL **131**, 211001

11

Qubit $\int \mathcal{H}/\hbar = (\omega_c + g^2/\Delta) \sigma_z/2 + (\omega_q + g^2/\Delta \sigma_z) a^{\dagger} a$ σ_z + $\omega_c a^{\dagger} a$ + $g(\sigma_+ a + a^{\dagger} \sigma_-)$ Cavity Qubit Interaction $|n = 1, e\rangle$ $|n = 1, g\rangle$ $|n = 0, g\rangle$ $|n = 0, e\rangle$ ω_c $+ \omega_c$ (*e*) $\omega_c^{(e)}$ *c* $\omega_c^{(g)}$ *c* $\omega_c^{(g)} \neq \omega_c^{(e)}$ $\Delta = \omega_c - \omega_q$

Dispersive readout

Cavity

 $\mathcal{H}/\hbar = (\omega_c + g^2/\Delta)\sigma_z/2 + (\omega_q + g^2/\Delta\sigma_z) a^{\dagger}$ *a*

 $\mathscr{H}/\hbar =$ *ωq* 2

- Dispersive readout

the standard method for quantum computing

- Direct excitation experiments utilize this interaction

$\sigma_z + \omega_c a^{\dagger} a + g(\sigma_+ a + a^{\dagger} \sigma_-)$

Lamb shift

Cavity

 $\mathcal{H}/\hbar = (\omega_c + g^2/\Delta)\sigma_z/2 + (\omega_q + g^2/\Delta\sigma_z) a^{\dagger}$ *a*

estimated qubit frequency changes $\Delta = \omega_c - \omega_q$ changes ω_c

 $\rightarrow \omega_c$ can tune by tuning ω_c can tune by tuning ω_q

 $\mathscr{H}/\hbar =$ *ωq* 2 $\sigma_z + \omega_c a^{\dagger} a + g(\sigma_+ a + a^{\dagger} \sigma_-)$

Cavity→(mode crossing)→Qubit The tuning range is determined by *g*

Lamb shift experiment

Readout by like a standard DM experiments

Solenoid Coil

SID-type qubits

Tuning of qubit frequency is easy Just applying external small magnetic field to the squid loop

B-field

Lamb shift simulation

Interaction Maximum **Interaction Minimum**

Courtesy of Kan Nakazono

16

Direct Excitation

Dark photon converts to E-field by any metal surfaces (ex. shield of qubits)

2. Qubit state is driven from |0> to |1> by the E-field if the qubit frequency matched to the E-field frequency ~ Dark photon Compton frequency

3. The state is read out by dispersive readout (exactly the same way as quantum computing)

Courtesy of Karin Watanabe

idea from Moroi +, PRL 131.211001

Setup We can do both experiment with the same setup!

17

Well-established measurement methods in haloscope experiments

Setup We can do both experiment with the same setup!

Lamb shift experiments

Tunable qubit frequency

Lamb shift experiments The parameters of our setup

$$
P_{A'} = \eta \chi^2
$$

 $P_{noise} \sim \frac{k_b b T_{sys}}{\sqrt{N}}$

cplanation photon mass hoton density nna coupling andwidth stem noise ctive volume) quality factor uation factor ple number

 ${P_{A^{\prime}}}{\rho_{A^{\prime}}}{V_{eff}}{\cal Q}_{L} \mathop =\limits_{\cal A}$ ρ + 1

Courtesy of Kan Nakazono

others $8.733 \,$ GHz= $36.1 \, \mu$ eV SJ Asztalos et al. (2001)

setting of spectrum analyzer extrapolate hotload measurement $V \times$ formfactor

Lamb shift experiments \mathcal{L} , we have a set \mathcal{L} of \mathcal{L} and \mathcal{L}

90% exclusion limit

coupling (g)

 \rightarrow 1-2 GHz tuning is possible at least in the simulation

realized by galvanic contact [Noguchi+ 2016](https://iopscience.iop.org/article/10.1088/1367-2630/18/10/103036/pdf)

-
-

Much better sensitivity shift of the material of the photon of the photon \mathbf{r}_1 dent de roum de province de la personaliste is 2 per provinciale de la personaliste de la personaliste de la p
Entre la personaliste de la persona the data matter and electromagnetic field results in a photon would he realized by reveals to storage called a σ ship of the monoton of the single dependent shift is 2 per photon. Much better sensitivity would be realized by combining with single Ultimate coupling could be

realized by galvanic contact

Direct Excitation Experiment

Basic checks for $|0\rangle$ $|1\rangle$

discrimination

Artificial signal

Courtesy of Karin Watanabe

Direct Excitation Experiment

Courtesy of Karin Watanabe

GHz

Future plan for direct excitation

 λ hopel in a passes of a field to the reach with = 1 (100) using *n*^q = 1 and *n*^q = 100, respectively, where the individual \mathbf{m} is applied. On the orange contour co in parallel to O(10) T → Applying magnetic field

by a linear composition in the following forms of the following forms of the following forms of the following \mathbf{r} leads sensitivity increase by N^2 Sichanugrist+

Towards Axion Search

Photon transfer

Pros: Easer, Cons: Potentially lossy Pros: No loss

arXiv:2403.02321

B-field tolerant qubits

Cons: More difficult

Qubits worked at least 1T

J. Krause et.al., Phys. Rev. Applied 17, 034032 (2022)

Difficulty

- Critical field
- Suppression of Josephson effect

Solution: All-nitride qubits

T. Polakovic, APL Materials 6 (2018) 076107

NbN 240 nm film

Nitride has high $Tc2 \rightarrow$ We don't have to care about critical field fabout clitical in

Suppression of Josephson Effect E_{max} OI J OSEDII SOII LILECT profile of Imax in Figure 12.5 is formally identical to the diffraction figure of light *320 SUPERCONDUCTIVITY* Qualitatively, the occurrence of a variation of the maximum intensity as a function of external field in agreement with the FRAUNHOFER diffraction pattern is the sig- \bullet and occurrence of a variation of the maximum intensity as a function of the maximum intensity as a OCCIAN AT IACANAC nature of the quality of a JOSEPHSON junction, in particular that it is uniform over H *i* and *^I*² г *I* / 2 ϵ ext, and in so far as the injected $\overline{}$

C $\sqrt{ }$

$\sqrt{2}$ **Figure 12.6 - Profiles of the JOSEPHSON current density** a koop the erecception to the 10 T = 1 flux quantum / $(14$ nm $)^2$ across the insulation in the insulation of the insulation in the magnetic field \mathcal{L} **(a, b, c, d)** distribution of the JOSEPHSON current across the insulator when the intensity **(d, e)** for the same value of J the junction "adjusts" the phase -(0) to the current

 $\frac{1}{2}$

 \rightarrow Have to keep the cross-section to the magnetic field small

Current Status

TiN 2D resonator

Summary

- Superconducting qubit is a promising platform for DM search

-
- We did two experiments
	-
	- Direct excitation (Lead by Karin Watanabe) - Lamb shift tuning (Lead by Kan Nakazono)
- We are working on
	- Larger electric dipole coupling qubits for wider tuning range for Lamb shift & better sensitivity for direct exitation - Applying strong magnetic field in parallel to thin film for axion
		-
	-