Origin and Suppression of 1/f Magnetic Flux Noise

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Outline

• 1/f flux noise in superconducting circuits (SQUIDs, qubits)
• Evidence for surface magnetic defects
• XAS and XMCD: magnetism from adsorbed O$_2$
• Suppression of surface magnetism: susceptibility and flux noise
• Recent theoretical progress
• Some details (geometry, materials dependence of noise)
• Future directions
1/f Flux Noise in SQUIDs

[Wellstood et al., APL 50 772 ('87)]

Hypothetical noise source

- Noise from SQUID(2) or \( I_{o1} \)
- Noise from \( I_{o1} \)
- Symmetric fluctuations in \( I_{o1} \) & \( I_{o2} \), \( R_1 \) & \( R_2 \), or \( L_1 \) & \( L_2 \)
- Antisymmetric fluctuations in \( I_{o1} \) and \( I_{o2} \)
- Antisymmetric fluctuations in \( L_1 \) and \( L_2 \)
- Antisymmetric fluctuations in \( R_1 \) and \( R_2 \)
- Fluctuations in external magnetic field
- Noise from substrate
- Noise from SQUID support
- Liquid helium in cell
- Heating effects
- Motion of flux lines trapped in SQUID

Properties of source

- Noise would not appear as flux noise
- Noise would depend on \( M_i \)
- Noise would not appear as flux noise
- \( S_\Phi \) would scale as \( I^2 \)
- \( S_\Phi \) would scale as \( \Phi^2 \)
- \( S_\Phi^{1/2} \) would scale as SQUID area
- Should depend on material
- Should depend on material
- Should change in absence of helium
- Should depend on power dissipated
- Should depend on material

“universal” 1/f flux noise

no clear dependence on materials

mechanism unknown
Dephasing from $1/f$ Noise

\[ S_\lambda = \frac{A}{\omega} \]

Ramsey fringes

\[ f_{\text{Ramsey}}(t) = \langle \exp(i\Delta \phi) \rangle = \exp \left( -\frac{1}{2} \langle \Delta \phi^2 \rangle \right) \]

\[ \langle \Delta \phi^2 \rangle = \left( \frac{\partial \omega_z}{\partial \lambda} \right)^2 \left( \int_0^t dt' \delta \lambda(t') \int_0^{t'} dt'' \delta \lambda(t'') \right) \]

\[ = \left( \frac{\partial \omega_z}{\partial \lambda} \right)^2 \left( \int d\omega \, S_\lambda(\omega) \text{sinc}^2(\frac{\omega t}{2}) \right) t^2 \]

\[ S_\lambda = \frac{A}{\omega} \]

\[ \langle \Delta \phi^2 \rangle = 2 \left( \frac{\partial \omega_z}{\partial \lambda} \right)^2 A \ln \left( \frac{1}{\omega_m t} \right) t^2 \]  

(not a rate)

\[ f_{\text{Ramsey}}(t) = \exp \left[ -\left( \frac{\partial \omega_z}{\partial \lambda} \right)^2 A \ln \left( \frac{1}{\omega_m t} \right) t^2 \right] \]

Gaussian decay envelope

\[ T_2^* = 90 \text{ ns} \]
### 1/f Flux Noise in SC Qubits

**Phase qubit**

- $L = 720$ pH
- $S_{\phi}^{1/2} (1 \text{ Hz}) = 2-4 \mu\Phi_0/\text{Hz}^{1/2}$
- (UCSB)

**Flux qubit**

- $L = 3 - 5$ pH
- $S_{\phi}^{1/2} (1 \text{ Hz}) = 1 \mu\Phi_0/\text{Hz}^{1/2}$
- (NEC, NTT)

**Also:**

- Investigations of dressed dephasing (Siddiqi et al.): probe to 100s MHz
- Evidence for magnetic loss at GHz frequencies (Lincoln, Google)

**Universal flux noise?** Compatible with earlier SQUID measurements
Surface Magnetism in SC Devices

\[ B_{\text{cool}} \]

\[ T > T_c \]

\[ T < T_c \]

\[ \sigma_{\text{vortex}} \approx \frac{B_{\text{cool}}}{\Phi_0} \]
Temperature-dependent flux scales linearly with density of vortices.
Interpretation: Polarization of Unpaired Spins in Vortex

\[ B_{\text{vortex}} \approx 40 \text{ mT} \quad T \sim \frac{\mu_B B_{\text{vortex}}}{k_B} \sim 30 \text{ mK} \]

• Circulating current decreases due to flux quantization
• Flux coupled to vortex by polarization of spins \( \sim 10 \mu \Phi_0 \)
• Substantial fraction of the vortex current couples to the SQUID

1: Calculate flux coupled to SQUID from vortex
2: Calculate flux coupled to vortex from uniform density of spins

[Sendelbach et al. arXiv:0802.1511 (08)]
Interpretation of Field Cool Data

Polarization of unpaired spins in vortex

\[ B_{vortex} \approx 40 \text{ mT} \]

\[ T \sim \frac{\mu_B B_{vortex}}{k_B} \sim 30 \text{ mK} \]

\[ \Delta P_{eff} = \text{Change in effective spin polarization} \]

\[ \sigma_S = \text{Spin Density} \]

\[ \frac{\Delta \Phi}{B_{fc}} = 0.14 \frac{A_{SQ}}{\Phi_0} \mu_B \sigma_S L_v \Delta P_{eff} \]

Implies: \[ \sigma_S = 5 \times 10^{17} \text{ m}^{-2} \]

compatible with Bluhm et al.

Rogachev et al.
Theoretical Models

L. Faoro and L.B. Ioffe [PRL 100, 227005 (08)]

- spins at S-I interface (surface density of spins $\sigma \sim 10^{16}$-$10^{17}$ m$^{-2}$)
- RKKY interaction, spin diffusion in nonuniform current distribution of SQUID

Choi et al. [PRL 103, 197001 (09)]

- disordered metal-insulator interface
- Localized metal-induced gap states (MIGS); density $\sigma \sim 5 \times 10^{17}$ m$^{-2}$
Investigations of Surface Spin Susceptibility

Rich, history-dependent structure in $\Delta L(T)$

Correlated fluctuations of $L$ and $\Phi$ (susceptibility and magnetization)

Sendelbach et al., PRL 103 117001 (09)
X-ray Magnetic Circular Dichroism (XMCD)

- Element-specific spectroscopic probe of magnetism
- Good sensitivity to surface/interfacial spins

• Absorption of LHCP and RHCP X-rays by polarized sample
• Total Electron Yield (TEY): sensitive to surface magnetism
• Total Fluorescence Yield (TFY): sensitive to bulk magnetism

User proposal to Argonne National Lab
[co-PIs Pappas (NIST); Yu, Wu (Irvine); Freeland (ANL)]

Argonne beamline 4-ID-C:
7 T field at 4.2 K (unique in the US)

Look at native Nb, Al, SiOx/SiNx encapsulated Nb, Al

www-ssrl.slac.stanford.edu/stohr/xmcd.htm
No signature of magnetism on native samples cooled in the UHV cryostat of the end station!
X-ray Magnetic Circular Dichroism (XMCD)

Strong XMCD signal from O K-edge following adsorption of air on the sample at low temperature (1e-6 Torr for ~1 min.)

Significant modification of O K-edge at ~ 45 K in O₂ partial pressure around 1e-8Torr
$O_2$ Magnetism

paramagnetic $O_2$
O$_2$ Magnetism

Long range AFM order

Helicoidal order

(a) $\alpha$-O$_2$

(b) $\beta$-O$_2$

Evolution of UHV Cell

• Commercial SS conflat parts, coated with TiN inside and out
• Commercial welded SMA feedthrus
Evolution of UHV Cell

- Welded Al box
- Explosively-joined Al-SS bimetal for CF flanges
Evolution of UHV Cell

- Machined enclosure from grade 5 titanium
- Single conflat gasket
- Weld-in hermetic SMA feedthrus
- Copper pinch tube for pumpout
Investigated treatments:

- UHV bake (120 C)
- UHV + UV irradiation (365 nm)
- UHV bake + NH$_3$ backfill (~100 Torr)
Suppression of Static Susceptibility

![Graph showing suppression of static susceptibility](image)

- Flux ($\Phi_o$) vs Temperature (mK)
- Lines represent different conditions:
  - Red circles: conventional vacuum, $B_{fc} +$
  - Red triangles: conventional vacuum, $B_{fc} -$
  - Blue circles: NH$_3$ exposed, $B_{fc} +$
  - Blue triangles: NH$_3$ exposed, $B_{fc} -$
Madison SQUID Noise Measurements

$2 \times \text{Al shielding}$

$\text{Al/AlOx/Al}$  

$\text{Nb/AlOx/Nb}$

$\Phi = n\Phi_0 :$  
$\frac{\mathrm{d} I}{\mathrm{d} \Phi} = 0$

$\Phi = (n \pm 1/4)\Phi_0 :$  
$|\frac{\mathrm{d} I}{\mathrm{d} \Phi}| = \text{max}$

typ. flux gain: 40-80
Madison SQUID Noise Measurements

- 2 layers SC shielding
- 1 layer cryogenic mu-metal
- Powder filters on all leads
- RC filters on bias leads of DUT
Madison SQUID Noise Measurements

Fit to form $A/f^\alpha + B$; extract $A$, $\alpha$
## Madison SQUID Noise Measurements

<table>
<thead>
<tr>
<th>Device</th>
<th>Treatment</th>
<th>Pre-treatment</th>
<th>Post-treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$S_\Phi(1\text{ Hz})$ ($\mu\Phi_0^2$/Hz)</td>
<td>$\alpha$</td>
</tr>
<tr>
<td>SiN\textsubscript{x-1}</td>
<td>UHV</td>
<td>2.0</td>
<td>1.0</td>
</tr>
<tr>
<td>SiN\textsubscript{x-2}</td>
<td>NH\textsubscript{3}</td>
<td>4.4</td>
<td>0.7</td>
</tr>
<tr>
<td>SiN\textsubscript{x-3}</td>
<td>UHV, UV</td>
<td>2.8</td>
<td>1.0</td>
</tr>
<tr>
<td>SiN\textsubscript{x-4}</td>
<td>NH\textsubscript{3} UHV, UV</td>
<td>8.2</td>
<td>1.2</td>
</tr>
<tr>
<td>SiN\textsubscript{x-5}</td>
<td>NH\textsubscript{3} UHV, UV</td>
<td>4.1</td>
<td>0.8</td>
</tr>
<tr>
<td>SiN\textsubscript{x-6}</td>
<td>NH\textsubscript{3} UHV, UV</td>
<td>1.7</td>
<td>1.0</td>
</tr>
<tr>
<td>SiO\textsubscript{x-1}</td>
<td>UHV, UV</td>
<td>13.4</td>
<td>0.5</td>
</tr>
<tr>
<td>SiO\textsubscript{x-2}</td>
<td>UHV, UV</td>
<td>6.5</td>
<td>1.0</td>
</tr>
<tr>
<td>SiO\textsubscript{x-3}</td>
<td>UHV, UV</td>
<td>4.8</td>
<td>0.7</td>
</tr>
<tr>
<td>SiO\textsubscript{x-4}</td>
<td>UHV, UV</td>
<td>3.0</td>
<td>0.8</td>
</tr>
</tbody>
</table>
Madison SQUID Noise Measurements

surface-treated devices

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**Graphs:**

- **Graph (c):**
  - $S_0$ (1 Hz) After Treatment vs. $S_0$ (1 Hz) Before Treatment.
  - Markers:
    - **Circles** for oxide encapsulation.
    - **Diamonds** for nitride encapsulation.
  - Lines:
    - Red line labeled x2.
    - Black line labeled x5.

- **Graph (d):**
  - $\alpha$ After Treatment vs. $\alpha$ Before Treatment.
  - Markers:
    - **Black Dot** for UHV.
    - **Green Dot** for UHV+NH3 backfill.
    - **Pink Dot** for UHV+UV.

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Noise Measurements

run-to-run variation

(a) $S_a (1 \text{ Hz}) \text{ After T. Cycle (} \mu \Phi_0^2/\text{Hz})$ vs. $S_a (1 \text{ Hz}) \text{ Before T. Cycle (} \mu \Phi_0^2/\text{Hz})$

(b) $\alpha \text{ After T. Cycle}$ vs. $\alpha \text{ Before T. Cycle}$

3 K cycle
- SiN$_x$ (red circle)
- SiO$_x$ (blue circle)

300 K cycle
- SiN$_x$ (red square)
- SiO$_x$ (blue square)
Magnetism of Adsorbed \( \text{O}_2 \)

(C.C. Yu, R. Wu)

For \( \text{O}_2 \) adsorbed on sapphire, spin polarization similar to free \( \text{O}_2 \) molecule

(C.C. Yu, R. Wu)

- Magnetization localized in plane perpendicular to molecular axis

- Calculated ferromagnetic exchange energy \( J = 1.6 \text{ K} \)

  (assumes 0.48 nm separation; DFT result for \( \text{O}_2 \) on c-\( \text{Al}_2\text{O}_3 \))

- Curie temperature \( T_c = 4.3 \text{ K} \)

\[
k_B T_c = (\frac{z}{3}) JS (S + 1)
\]
O₂ Exchange Coupling on Al-Terminated α-Al₂O₃

\[ J = E_{uu,uu} - E_{uu,dd} \]

Exchange Coupling (a negative value shows ferromagnetism)

- \( J = -10 \text{ meV (113 K)} \)
- \( J = -4.0 \text{ meV (48 K)} \)
- \( J = -2.7 \text{ meV (32 K)} \)
- \( J = -0.55 \text{ meV (6.4 K)} \)
- \( J = -0.46 \text{ meV (5.3 K)} \)

- **Ferromagnetic** exchange couplings depend on the relative orientation of O₂ molecules.
- **Ferromagnetic clusters** of varying size and coupling may exist due to random O₂ orientations frozen in at low temperatures.
Correlated noise in spin models (Ioffe, Faoro)

Main ingredients of the model:
- Ferromagnetic ground state
- Frustration (simple ferromagnets form domains)
- Broad range of interaction strength
- Random anisotropy

Example most studied (natural?):
RRKY + random anisotropy

\[ H = \sum J_{ij} \hat{S}_i \hat{S}_j + J_{an} \sum (n_i \hat{S}_i)^2 + h_{ac} \cos \omega t \]
\[ J_{ij} = \frac{\cos(kr_{ij}) - (kr_{ij})^2 \sin(kr_{ij})}{(kr_{ij})^{1/4}} \]

Qualitative picture: high energy objects, due to strongly interacting spin clusters where spins points away from the easy plane direction, live for a very long time and produce large noise.
Device Geometry, Layer Stack

(a) SiN$_x$/SiO$_x$ JJ Al SiN$_x$/SiO$_x$

(b) W = 40 µm
    R = 100 µm
    R/W = 2.5

W = 2 µm
    R = 20 µm
    R/W = 10

W = 2 µm
    R = 50 µm
    R/W = 25
Dependence of Noise on Device Geometry

**Simplified toroidal model of SQUID**

\[ \Phi_{dipole \rightarrow SQUID} = \frac{\mu_0 \mu}{2\pi r} \]

(reciprocity)

Expect \( S_\Phi \sim \sigma \ (R/r) \), apart from log corrections
Dependence of Noise on Device Geometry

(a)

\[ S_{\varphi}(\mu\Phi_0^2/\text{Hz}) \]

Frequency (Hz)

R/W \sim 25
R/W \sim 10
R/W \sim 2.5
Dependence of Noise on Device Geometry, Materials

- For devices co-fabbed on a single wafer, clear linear scaling of noise power with aspect ratio
- SiNx-encapsulated devices have lower noise
- No clear dependence of $\alpha$ on geometry or materials
Magnetic Activity of Adsorbed $O_2$

$\Delta E = 230 \text{ mK}$

$\Delta E = 460 \text{ mK}$

$\Delta E = 580 \text{ mK}$
Conclusions and Future Directions

• Adsorbed molecular $O_2$ the dominant contributor to low-frequency 1/f flux noise

• Need to care about the vacuum integrity of SC qubits!

• Open questions: effect of surface treatments on high-frequency part of 1/f flux noise spectrum

• Coming soon: integration with qubit circuits

arXiv:1604.00877