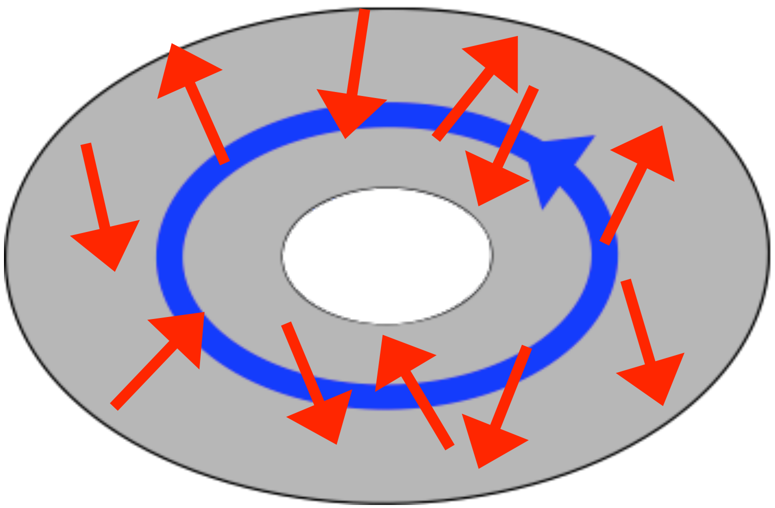
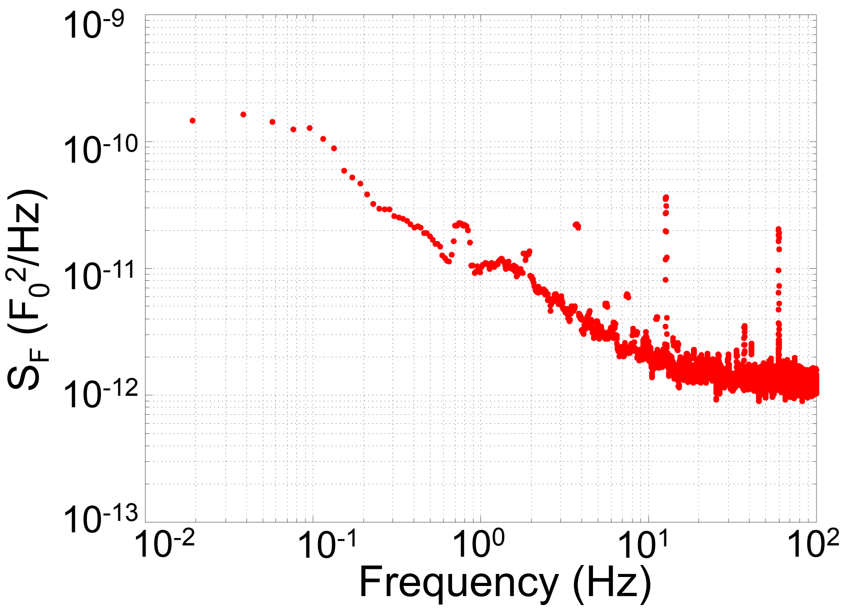
Flux Noise in Superconducting Qubits





Clare Yu,[1] Hui Wang,[1] Chuntai Shi,[1] Jun Hu,[1] Sungho Han,[1] Ruqian Wu,[1] Robert McDermott,[2] Pradeep Kumar,[2] John Freeland,[3] and David Pappas[4]

[1]UC Irvine, [2]Univ. of Wisconsin-Madison, [3]Argonne, [4]NIST

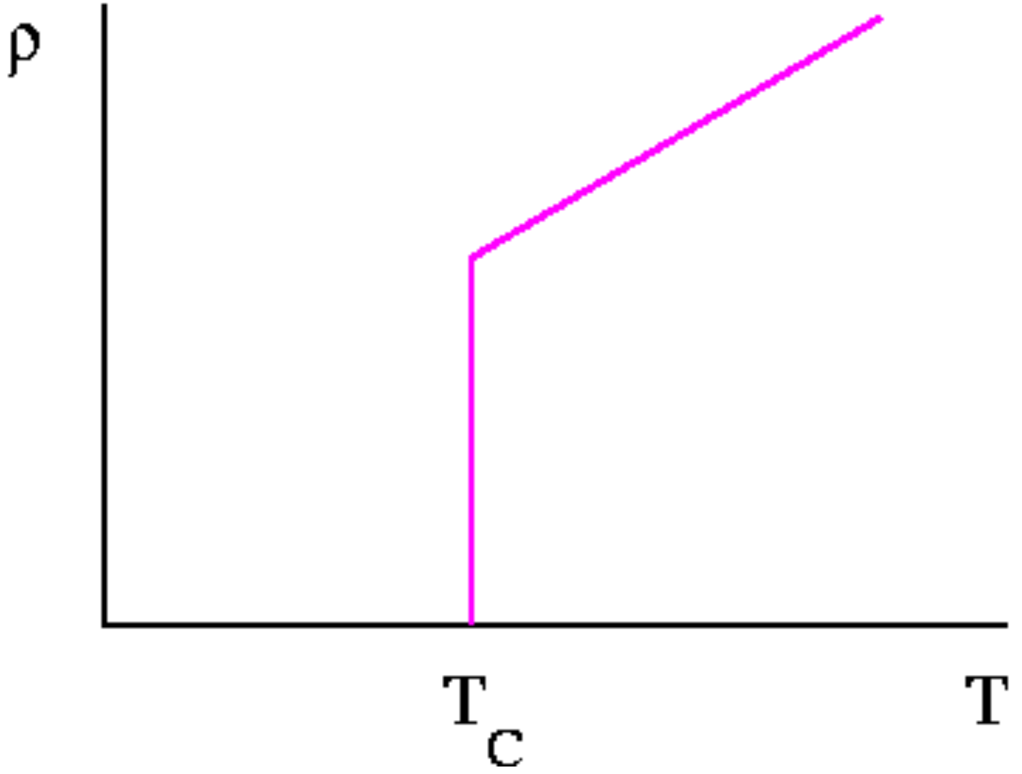
Sue Coppersmith’s recent work on quantum computing and quantum information

- Quantum dot hybrid qubit: hybrid between charge and spin silicon qubits (with Mark Eriksson, Mark Freisen, *et al*.)
- Quantum algorithms.

Introduction to Superconductivity

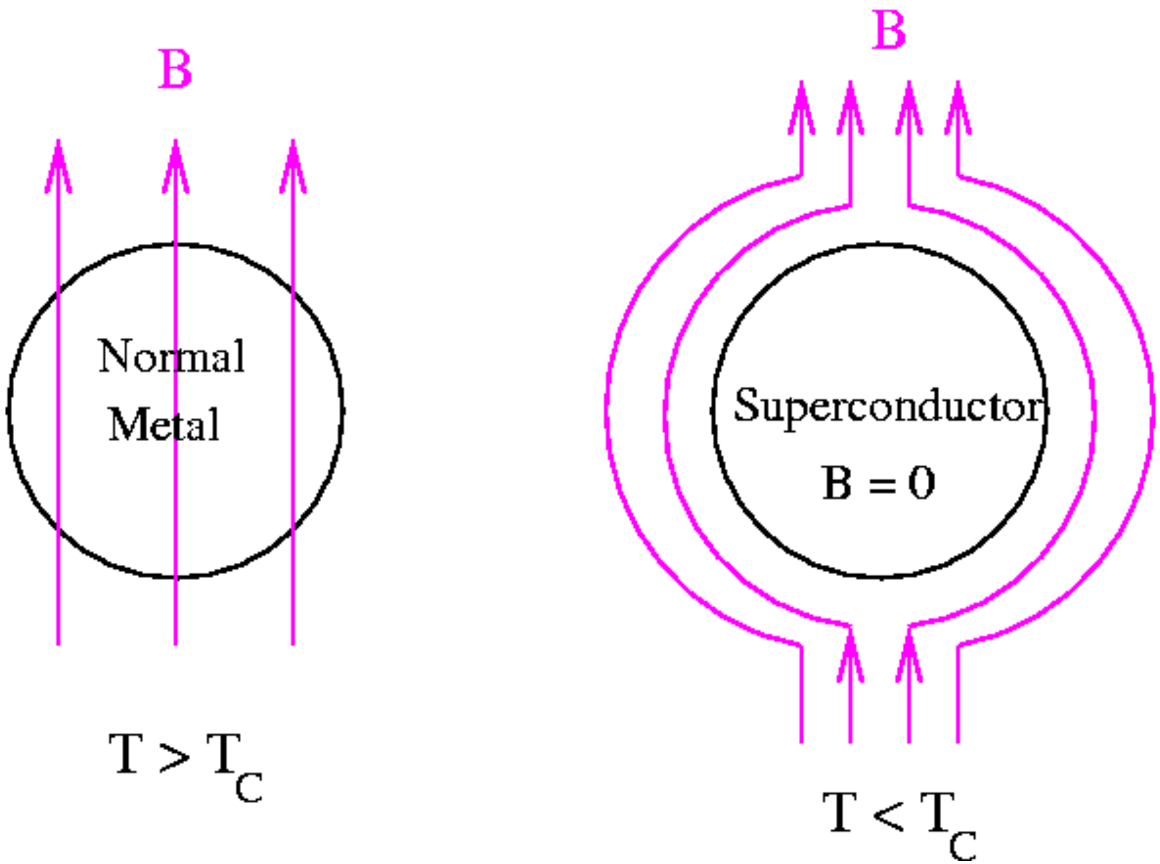
Superconductivity was discovered in 1911 by Kamerlingh Onnes.

•Zero electrical resistance



Meissner Effect

- Magnetic field expelled. Superconducting surface current ensures B=0 inside the superconductor.



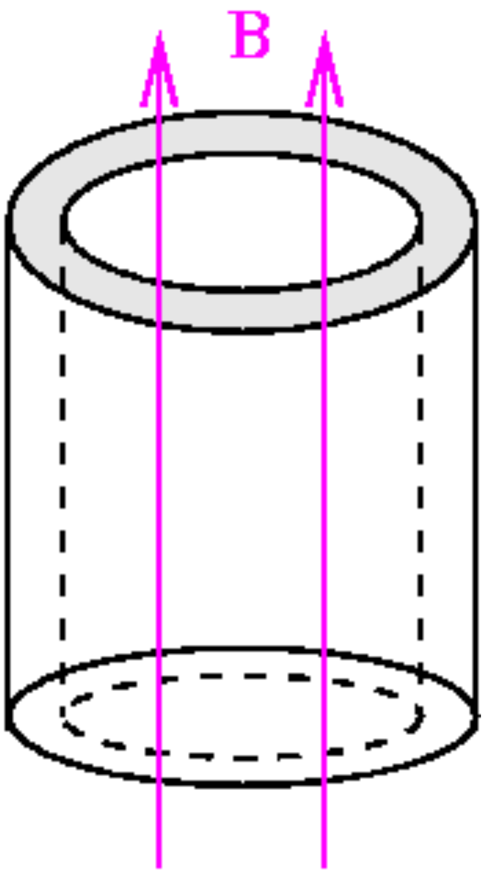
Flux Quantization

$$\Phi = \int \vec{B} \bullet d\vec{A} = n\Phi_o$$

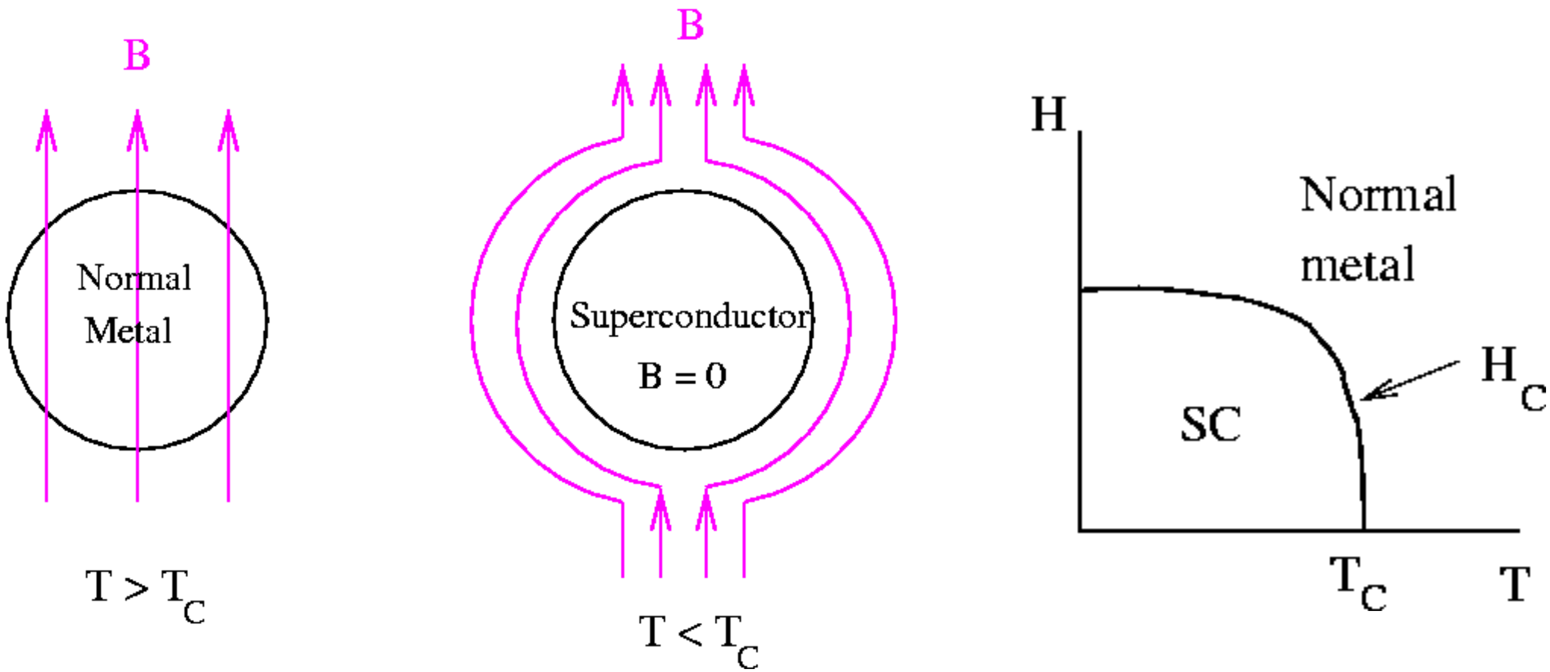
where the “flux quantum” Φ_o is given by

$$\Phi_o = \frac{hc}{2e}$$

$$= 2\times10^{-7}\ \text{gauss cm}^2$$



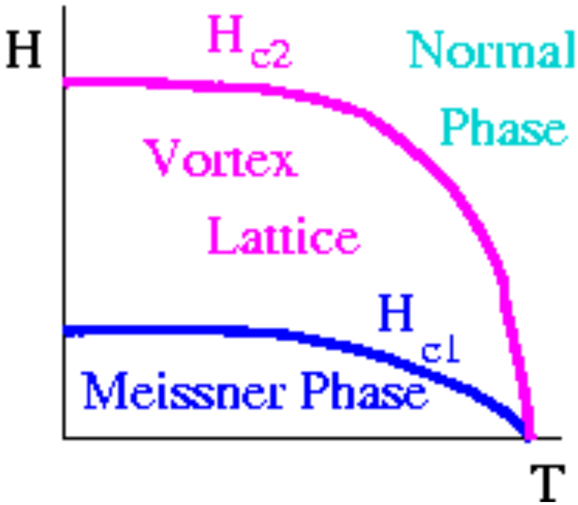
Type I Superconductors

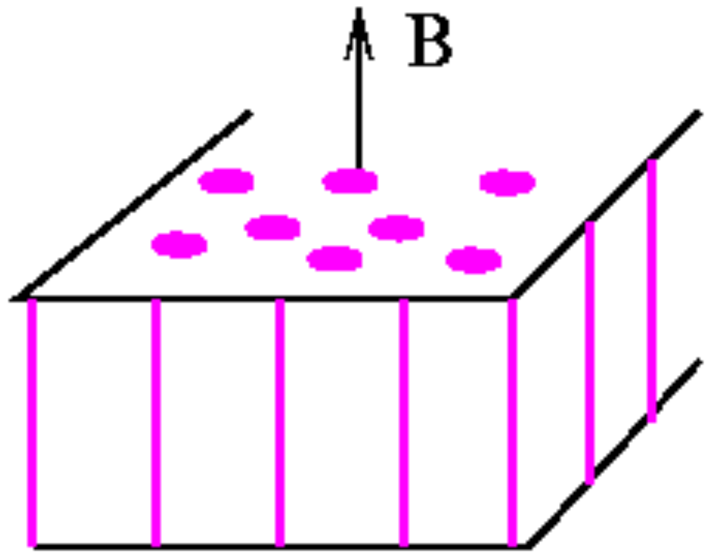


Type I superconductors expel the magnetic field totally, but if the field is too big, the superconductivity is destroyed.

Type II Superconductors

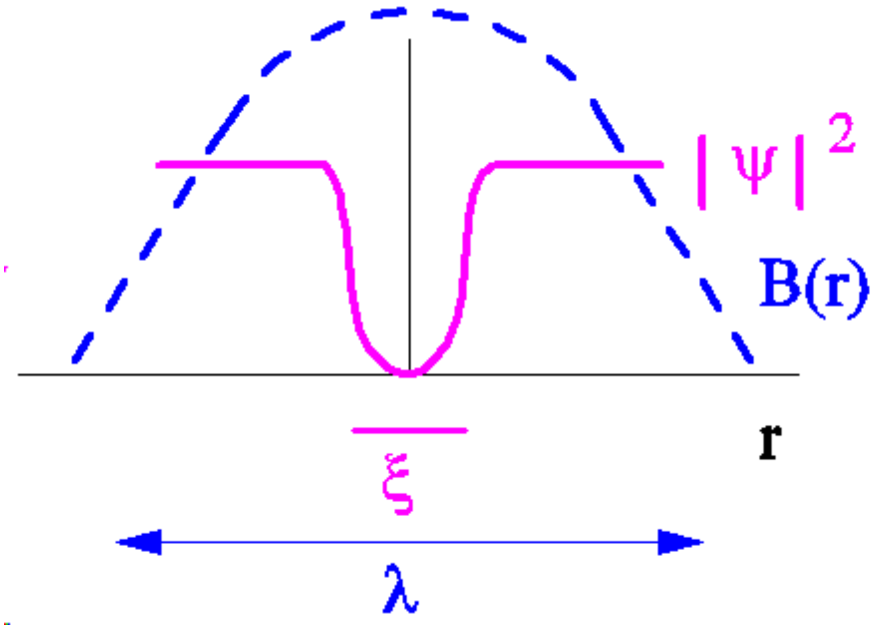
For intermediate field strengths, there is partial field penetration in the form of vortex lines of magnetic flux.

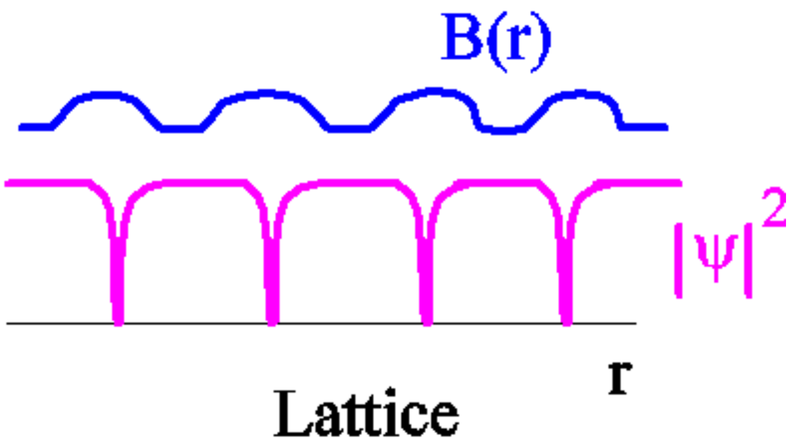




Vortices

Each vortex contains 1 flux quantum Φ_o=hc/2e. The superconducting order parameter goes to zero at the center of a flux quantum. The core of the vortex has normal electrons.



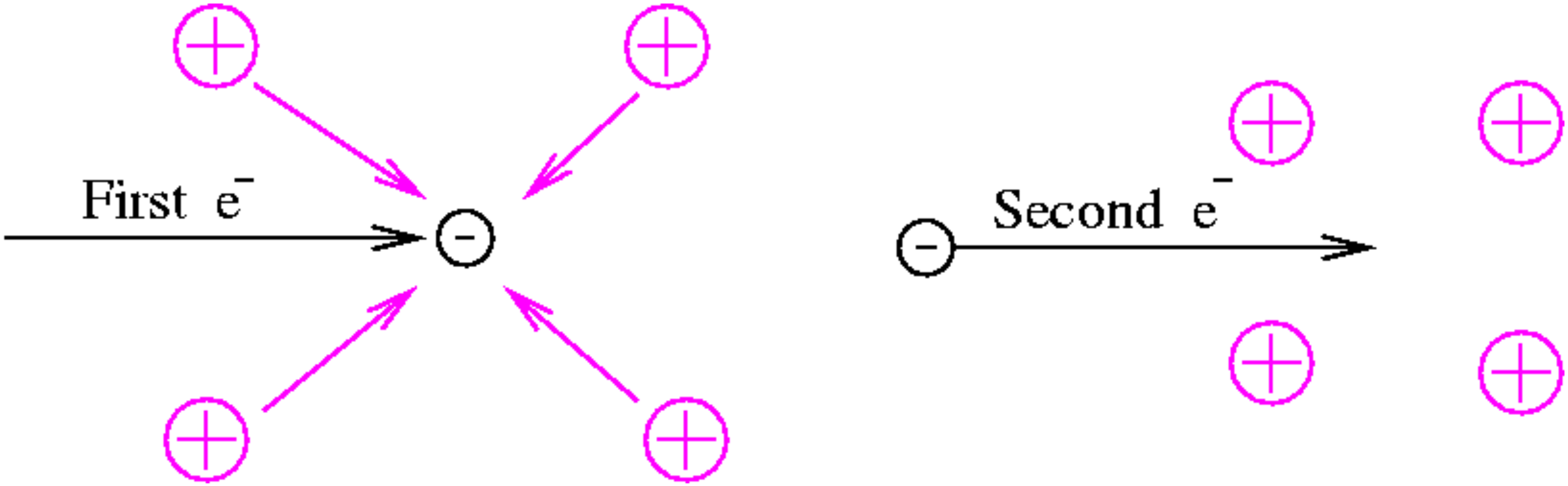


Explanation of Superconductivity

BCS Theory

(Bardeen-Cooper-Schrieffer)

- Electrons are paired into Cooper pairs.

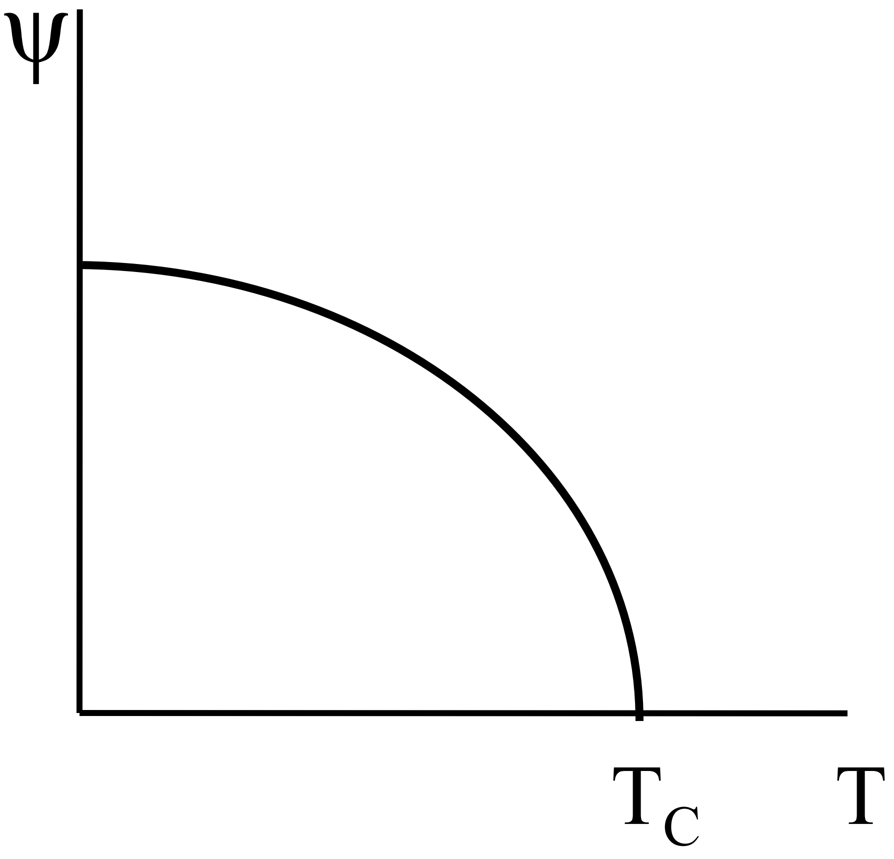


Explanation of Superconductivity

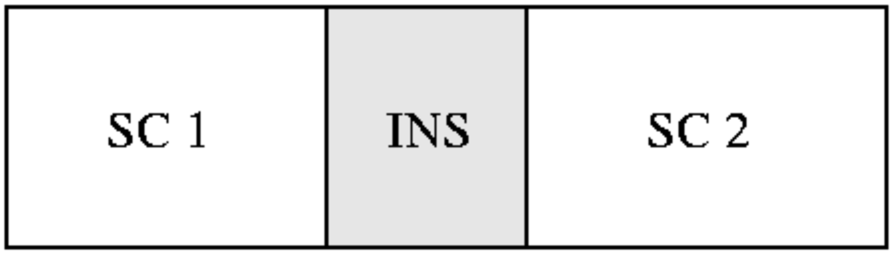
Ginzburg-Landau Order Parameter

$$\psi = |\psi| e^{i\theta}$$

Think of this as a wavefunction describing all the electrons. Phase θ wants to be spatially uniform ("phase rigidity").

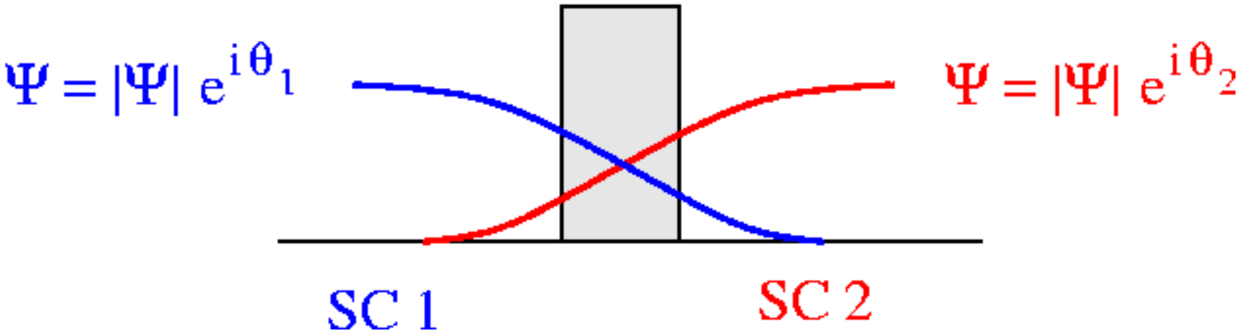


Josephson Effect



Josephson Tunnel Junction

If we put 2 superconductors next to each other separated by a thin insulating layer, the phase difference (θ_2-θ_1) between the 2 superconductors will cause a current of superconducting Cooper pairs to flow between the superconductors. Current flow without batteries! This is the Josephson effect.



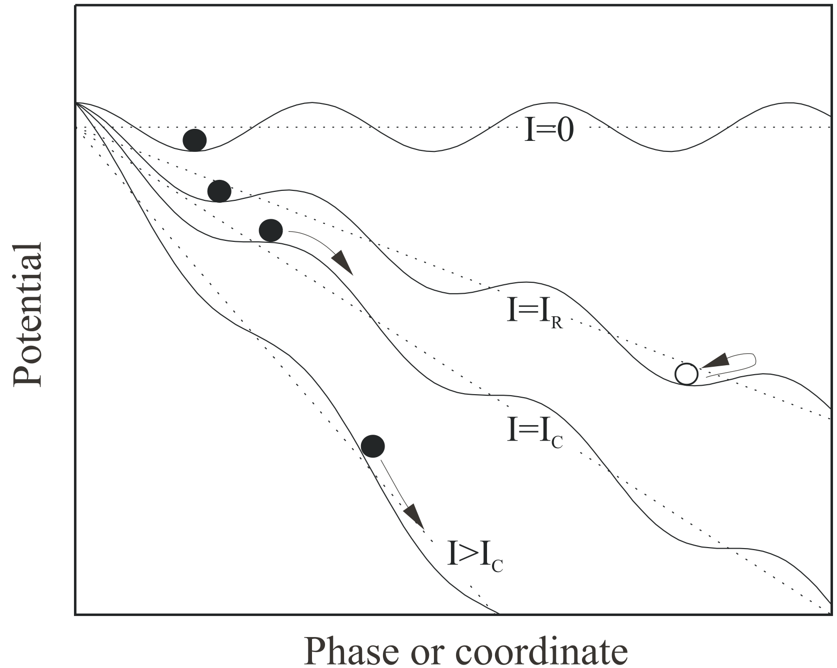
$J = J_o \sin(\theta_2 - \theta_1) = J_o \sin\delta$ where J_o is the critical current density and δ is the phase difference.

Josephson Junction Washboard Potential

$$J_o \sin\delta = \frac{2e}{\hbar}\frac{\partial U_J}{\partial \delta} \Rightarrow U_J = \frac{\hbar J_o}{2e} - \frac{\hbar J_o}{2e}\cos\delta$$

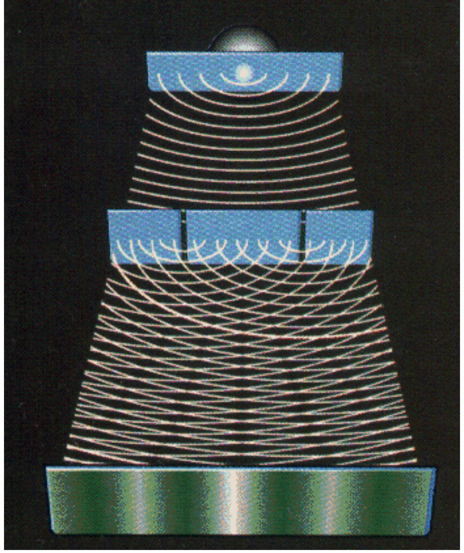
$$U_{tot} = \frac{\hbar J_o}{2e} - \frac{\hbar J_o}{2e}\cos\delta - \frac{\hbar J_{ext}}{2e}\delta$$

Washboard potential tilts with application of external current.

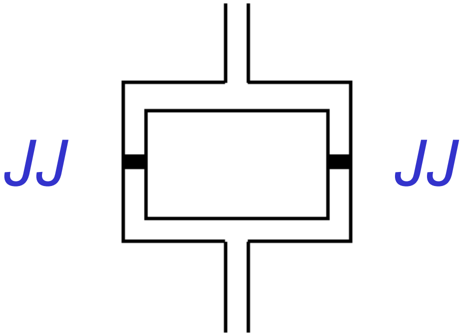


SQUIDs

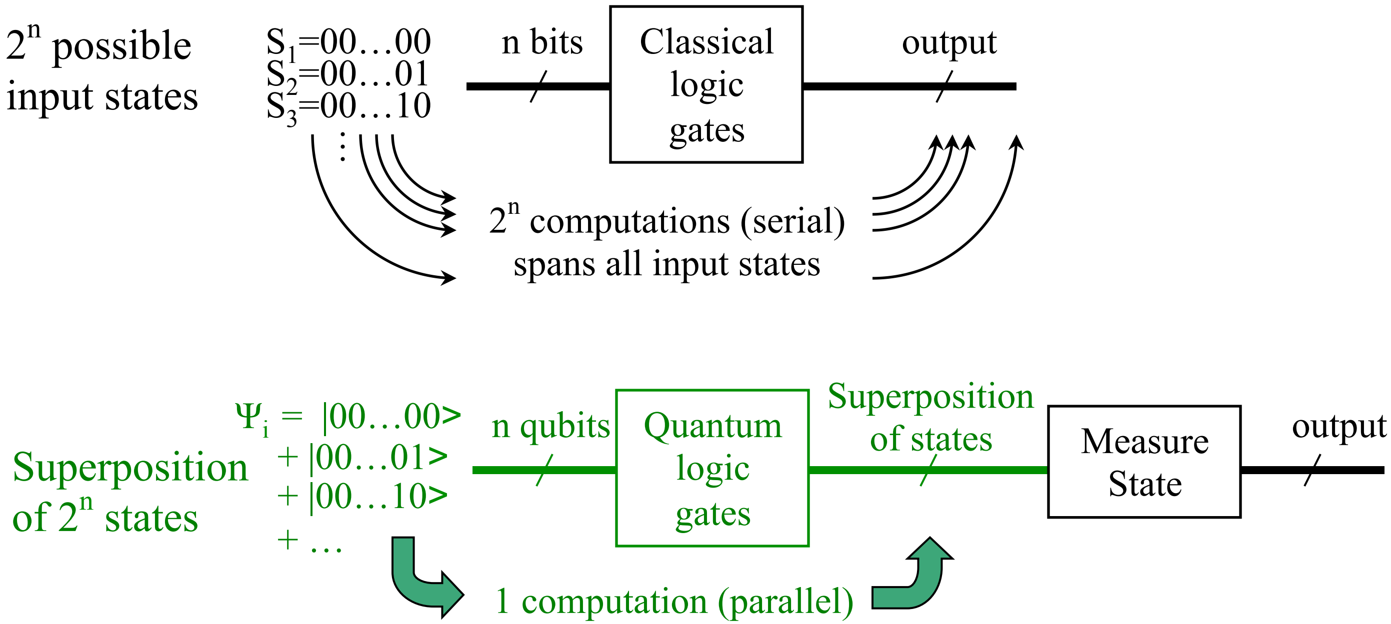
(~ 2 slit device for superconducting wave functions)



- SQUID is a Superconducting QUantum Interference Device.
- DC SQUID is a loop with 2 Josephson junctions.
- Phase difference around the loop proportional to magnetic flux through loop.
- Current through the SQUID is modulated by the magnetic flux through loop.
- SQUIDs are sensitive detectors of the amount of magnetic flux Φ through the loop.
- SQUIDs can be used as qubits (quantum bits).

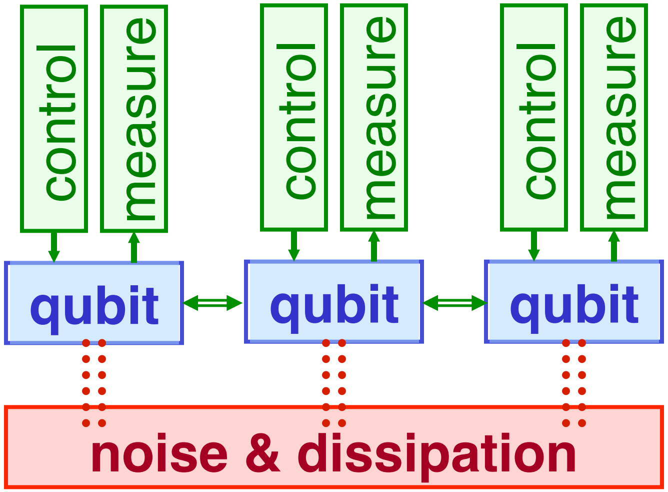


Why is Quantum Computing Useful?



- Parallel computation of exponentially-large states
- Factorization of large numbers into prime numbers (Shor) (cryptography)
  Exponential speedup of algorithm
- Fast search algorithms (Grover) { $n^{1/2}$ vs. n }
- Adiabatic algorithms for minimization (Farhi)
- Simulation of quantum systems (Feynman)
- Other? (Quantum Information Theory)

Challenge: Coupling vs. Decoherence



Experimental challenge:

Couple qubits to each other, and control, & measure,

Avoid coupling qubits to noise and dissipation

Qubit is a quantum bit

$$\Psi = \cos\frac{\theta}{2}\left|0\right\rangle + \sin\frac{\theta}{2} e^{i\phi}\left|1\right\rangle$$

Qubit wavefunction

Experimental Systems

Atoms **EM modes**

Feynmann (1985):

"it seems that the laws of physics present no barrier to reducing the size of computers until bits are the size of atoms, and quantum behavior holds sway."

- Photons

atomic

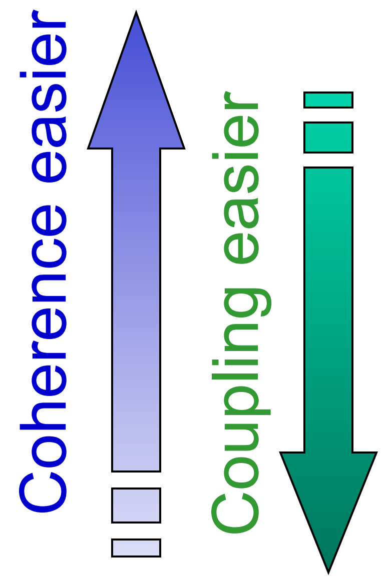
- Ions
- Neutral Atoms
- NMR

mesoscopic

- Spin
- Semiconductor spin
- Quantum Dot

microscopic

- Superconductor SET — **Charge** (NEC, Chalmers)
- 2-Degenerate SSET (Saclay)
- 3 Junction SQUID (Delft) — **Flux**
- RF SQUID (MIT)
- Josephson Junctions — **Phase** (NIST, Kansas)



Josephson Junction Qubit Taxonomy

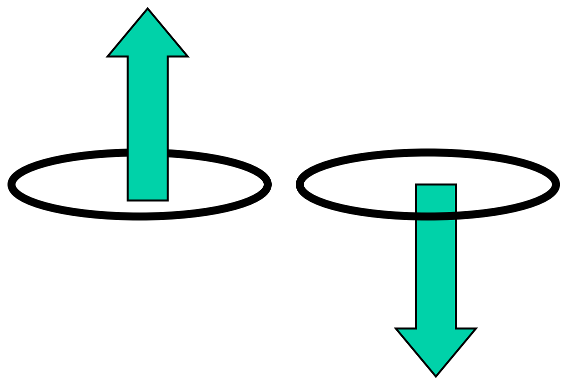
States are a linear combination of

Phase

2 different energy states in one well of JJ potential.

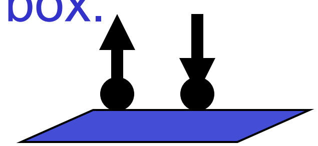
Flux

2 different flux states, e.g., up and down states of a SQUID.

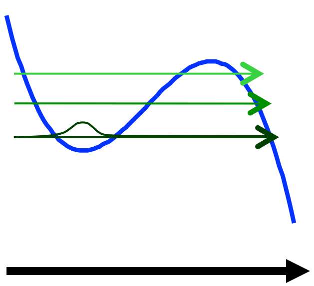


Charge

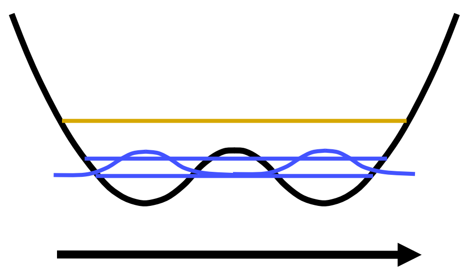
2 different charge states, e.g., n and (n +1) Cooper pairs in a Cooper pair box.



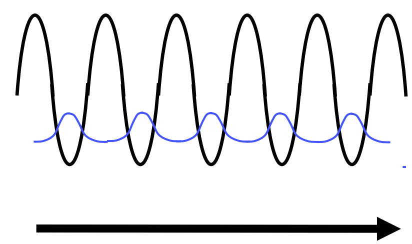
Potential & wavefunction



Phase difference δ



Flux Φ



Charge Q

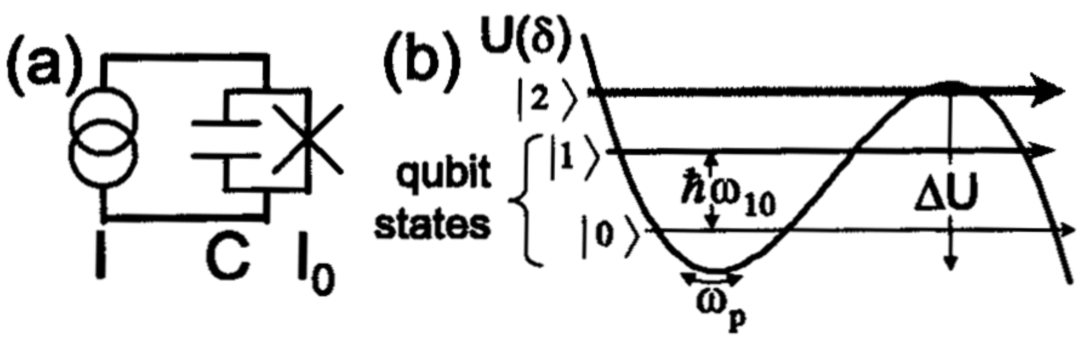
Quantum Computing and Qubits

Josephson junctions can be used to construct qubits.

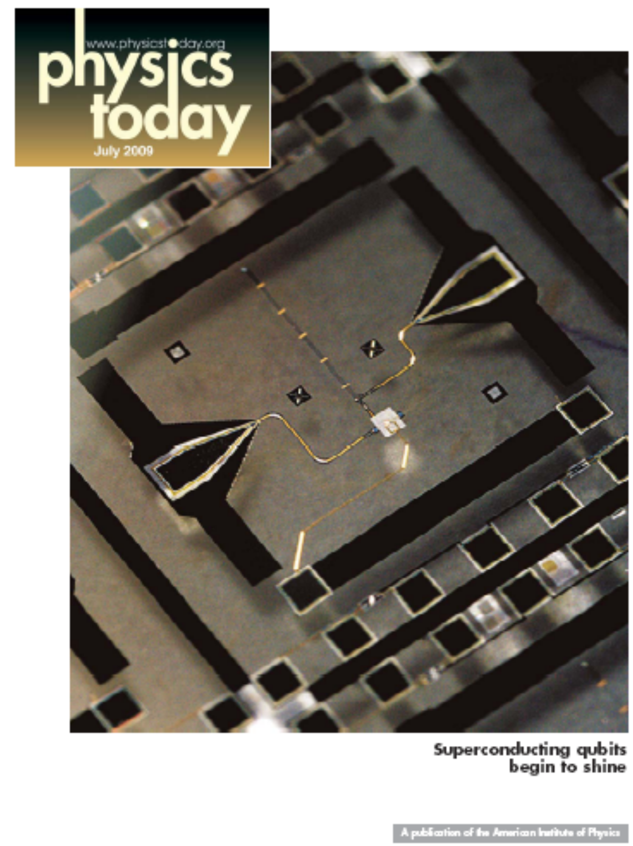
- Major Advantage: scalability using integrated circuit (IC) fabrication technology.
- Major Obstacle: Noise and Decoherence

$$\Psi = \cos\frac{\theta}{2}\left|0\right\rangle + \sin\frac{\theta}{2} e^{i\phi}\left|1\right\rangle$$

Qubit wavefunction

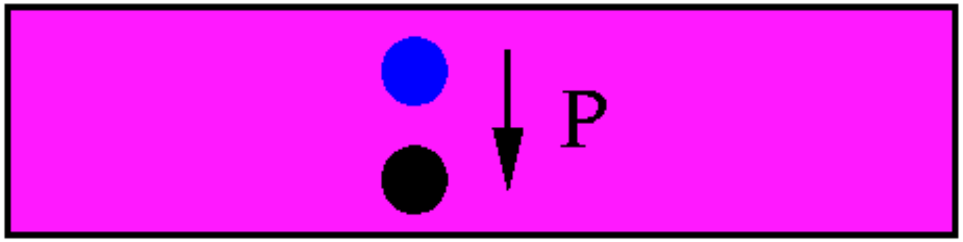


J. M. Martinis *et al.*, PRL 89, 117901 (2002).



Microscopic Sources of Noise

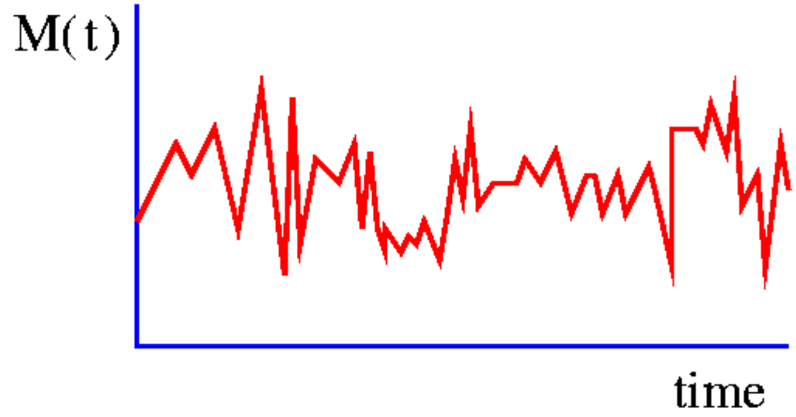
- Fluctuating charges, e.g., quasiparticles, electron hopping, electric dipoles flipping, two level systems
- Fluctuating magnetic spins
- Fluctuating magnetic vortices



Flux Noise
Is a Major Source of Noise and Decoherence in SQUIDs

Flux noise looks like fluctuating vortices or fluxoids in the SQUID, but that is not the source of flux noise at low temperatures. Magnetic spins on the surface of the SQUID are the source.

Noise Spectrum



Noise comes from fluctuations of some type. For example, let δM(t) be a fluctuation at time t. The autocorrelation function is

$$\psi_M(t) = \langle \delta M(t) \delta M(0) \rangle$$

The noise spectral density is proportional to the Fourier transform:

$$S_M(\omega) = 2\psi_M(\omega) = 2\int dt e^{i\omega t} \psi_M(t)$$

1/f noise dominates at low frequencies, and corresponds to

$$S_M(\omega) \sim \frac{1}{\omega}$$

(Actually "1/f noise" refers to S(f) ~ $1/f^{\alpha}$ where α is approximately 1 and f = frequency.)

1/f Noise Requires Distribution of Relaxation Times

Fluctuations in magnetization *M* lead to noise. We use the relaxation time approximation:

$$\frac{d\delta M}{dt} = -\frac{\delta M}{\tau} \Rightarrow \delta M = \delta M_0 e^{-t/\tau}$$

where $1/\tau$ is the relaxation rate.

$$\psi_M(t) = \langle \delta M(t)\delta M(t=0) \rangle$$

The Fourier transform is a sum of Lorentzians:

$$\psi_M(\omega) = A\int_{-D}^{D} \frac{\tau(\varepsilon,T)}{1+\omega^2\tau^2(\varepsilon,T)} g(\varepsilon,T)\,d\varepsilon$$

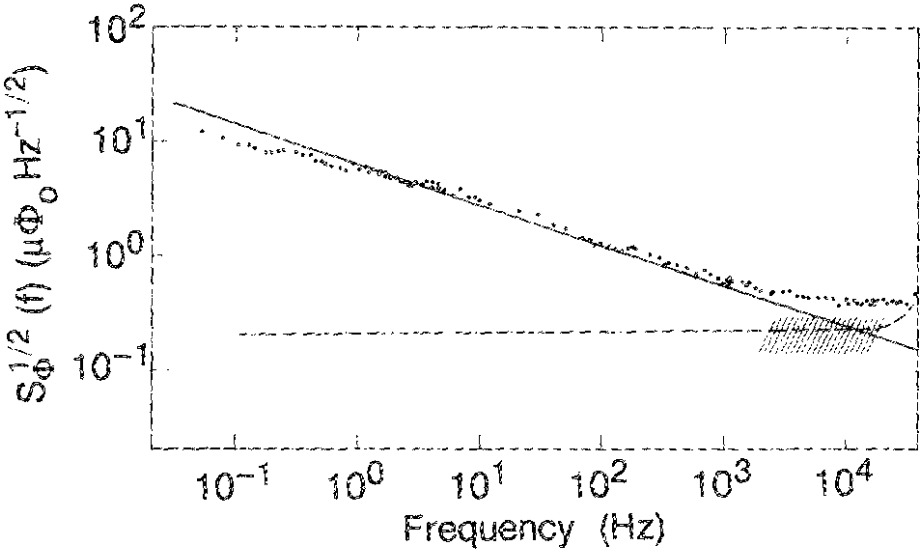
If we use $g(\varepsilon,T) = g_o$ for the density of states and $\tau = \tau_o e^{\varepsilon/kT}$ the noise spectral density is given by

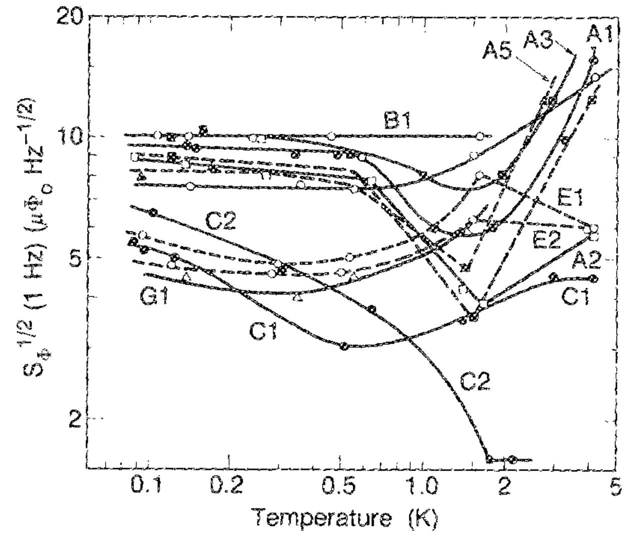
$$S_M(\omega) = 2\psi_M(\omega) \sim \frac{1}{\omega}$$

1/f Flux Noise in SQUIDs

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

$1/f^{\alpha}$ with $0.58 < \alpha < 0.80$





Hypothetical noise source	Properties of source
Noise from SQUID(2) or I_{b1}	Noise would not appear as flux noise
Noise from $I_{\Phi 1}$	Noise would depend on M_i
Symmetric fluctuations in I_{01} & I_{02}, R_1 & R_2, or L_1 & L_2	Noise would not appear as flux noise
Antisymmetric fluctuations in I_{01} and I_{02}	[a]
Antisymmetric fluctuations in L_1 and L_2	S_Φ would scale as I^2
Antisymmetric fluctuations in R_1 and R_2	S_Φ would scale as V^2
Fluctuations in external magnetic field	$S_\Phi^{1/2}$ would scale as SQUID area
Noise from substrate	Should depend on material
Noise from SQUID support	Should depend on material
Liquid helium in cell	Should change in absence of helium
Heating effects	Should depend on power dissipated
Motion of flux lines trapped in SQUID	Should depend on material

"Universal" *1/f* flux noise

Independent of : **inductance**
materials
geometry

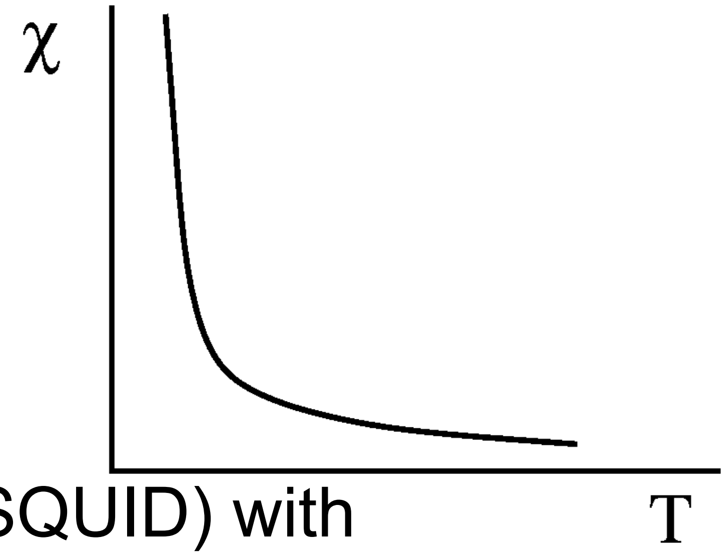
Not due to fluctuating vortices (seen in wires too thin to have a vortex)

Mechanism was unknown

Paramagnetic Susceptibility

Paramagnetism: Magnetization M is proportional to the magnetic field H

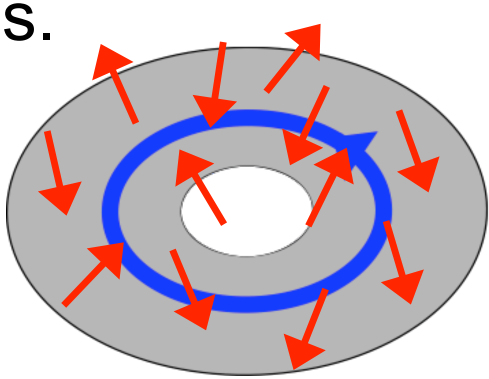
$$M = \chi H$$



Curie Susceptibility: $\chi \sim \frac{1}{T}$

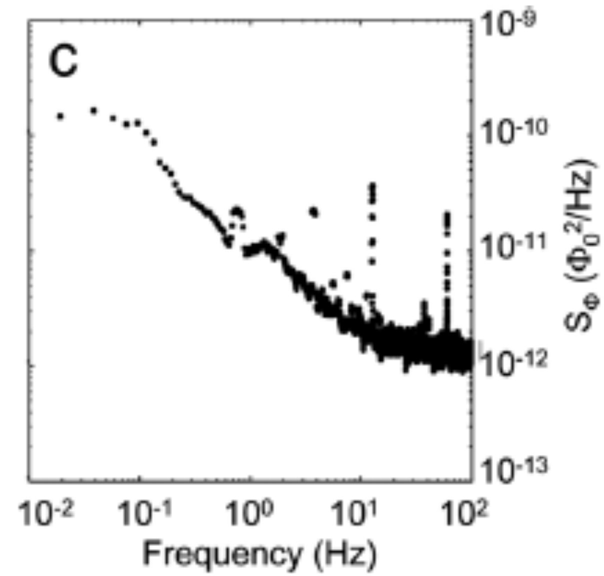
- Consider a toroidal current loop (SQUID) with spins on the surface.
- Current produces B field that polarizes spins.
- Polarized spins contribute to M and flux Φ.
- Flux Φ = LI ↔ Magnetization M = χH.

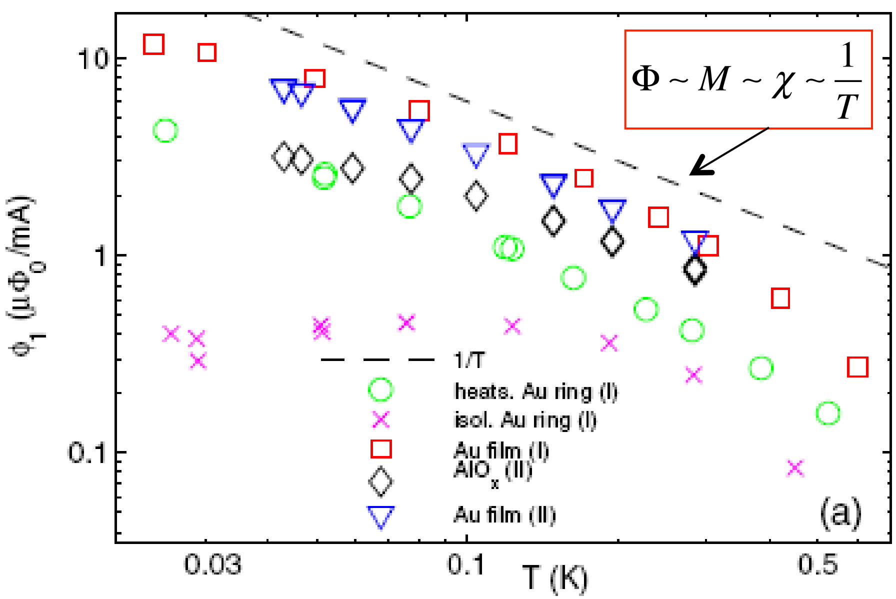
$$\Phi \leftrightarrow M, \quad L \leftrightarrow \chi, \quad I \leftrightarrow H$$



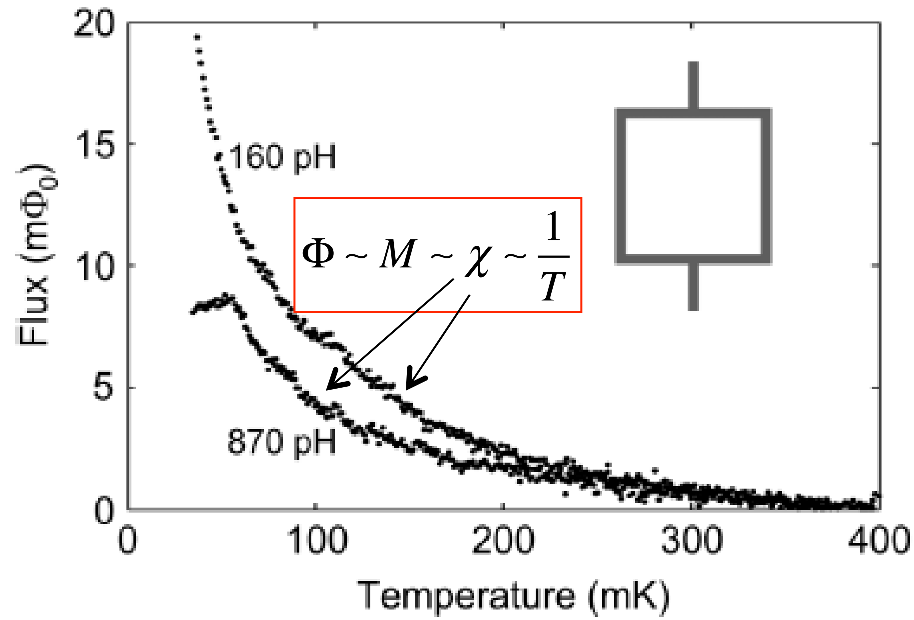
Flux Noise in SQUIDs

- Noise ~ $(1/f)^{\alpha}$ where $0.5 < \alpha < 1$.
- 1/f flux noise in SQUIDs is produced by fluctuating magnetic impurities.
- Paramagnetic impurities produce flux ~ 1/T on Al, Nb, Au, Re, Ag, etc.



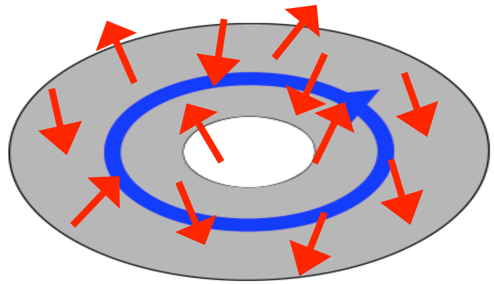


Bluhm *et al. PRL* (2009)



Sendelbach *et al. PRL* (2008)

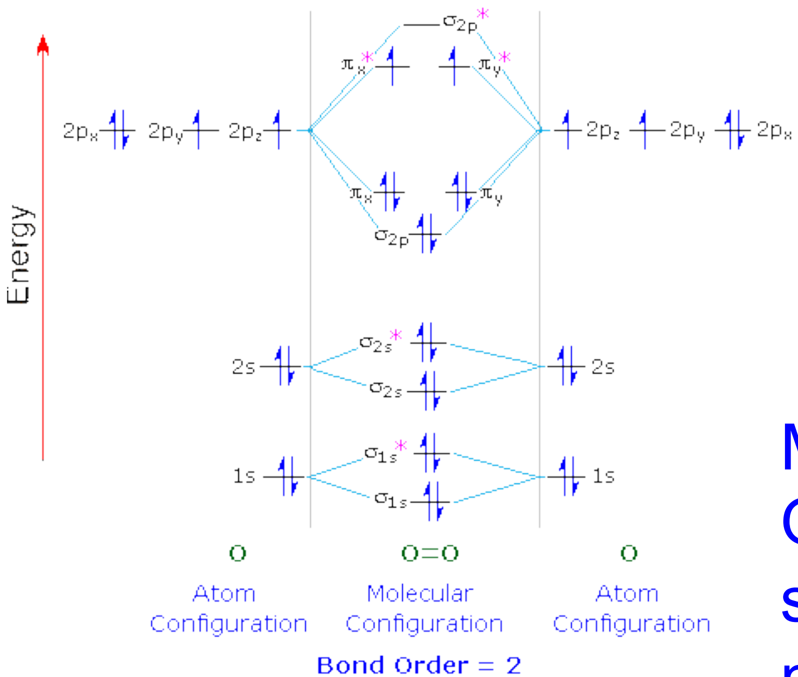
Evidence Indicates Spins Reside on Surface

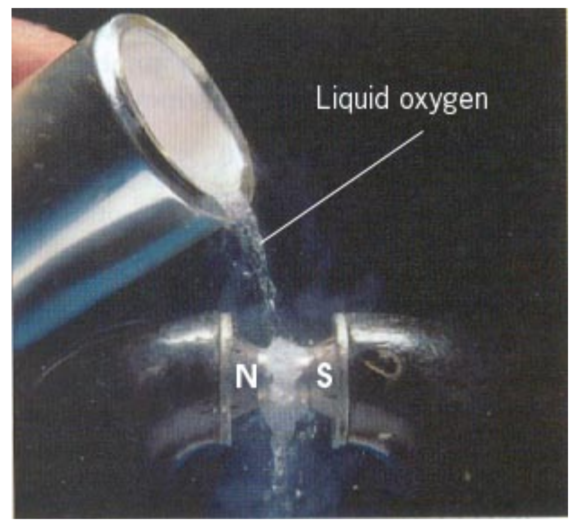


- Flux noise scales with surface area of the metal in the SQUID.
- Magnetic impurities in the bulk superconductor would be screened.
- Weak localization dephasing time τ_φ grows as T decreases (Bluhm *et al*.). If spin impurities in the bulk limited τ_φ, τ_φ would saturate at low T (Birge *et al*.).
- Concentration ~ $5\times10^{17}/m^2$ implies a spacing of ~1 nm between impurities if spin moment is 1 μ_B.
- May be due to electrons localized at the metal-insulator interface with magnetic moments (Choi *et al*.).
- Lee *et al.* proposed adsorbed neutral OH are the spins but spin reorientation barrier ~ 600 K.

Where do the spins causing flux noise come from?

- Oxygen (O_2) molecules adsorbed on the surface.
- Consistent with flux noise independent of material and scaling with surface area.



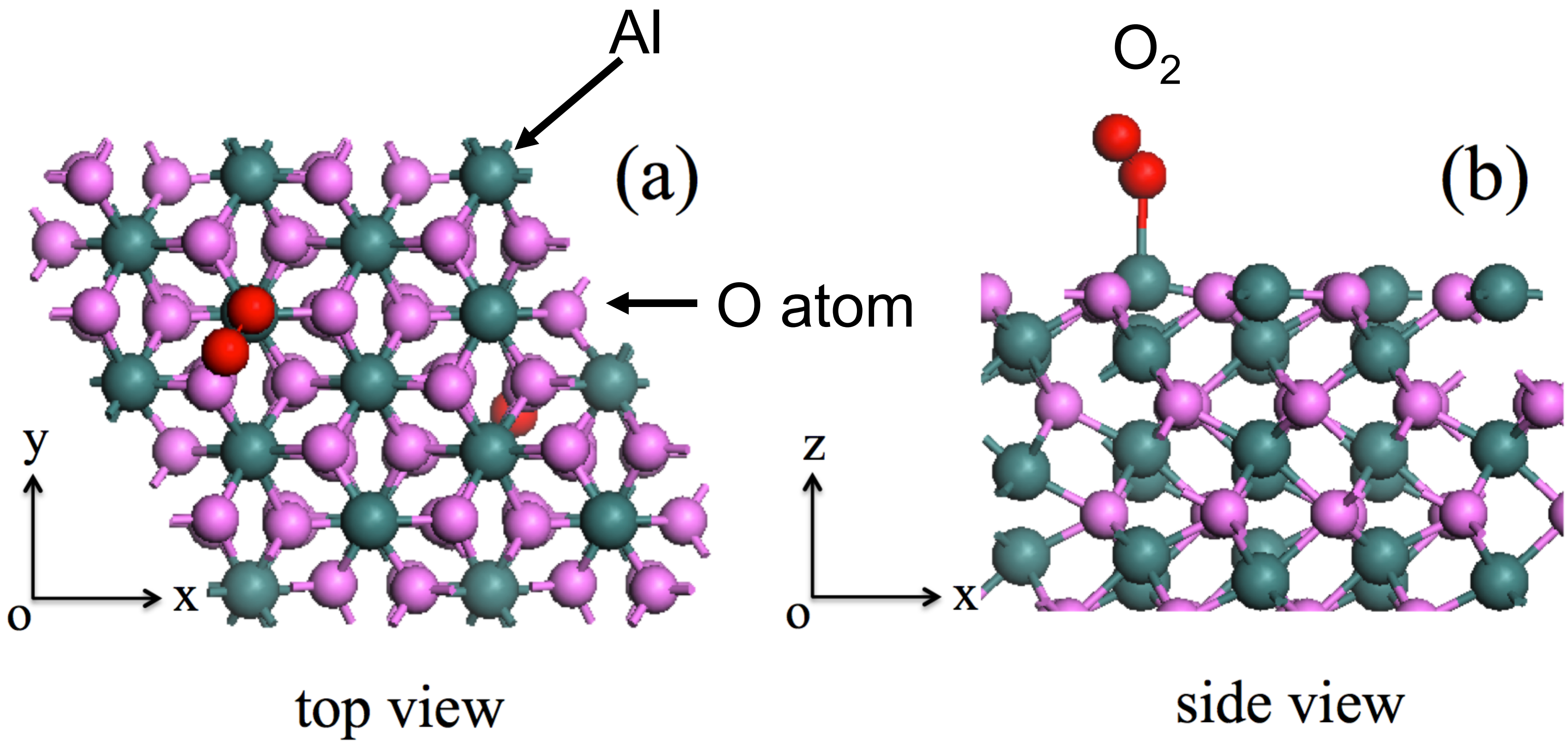


Molecular oxygen is paramagnetic. O_2 molecule has 2 unpaired electron spins in the triplet state (S=1) with magnetic moment = $2\mu_B$.

Are O_2 molecules adsorbed on the surface responsible for flux noise?

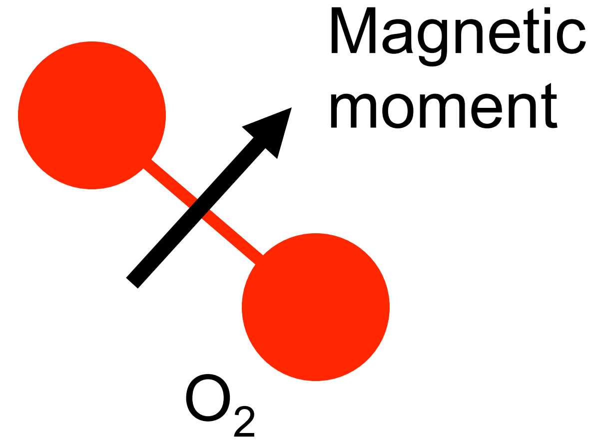
- O_2 molecules have S = 1 (mag. moment = $2\mu_B$)
- Oxygen weakly coupled to sapphire substrate (Al_2O_3)
- O_2 molecules sit on top of Al atoms.

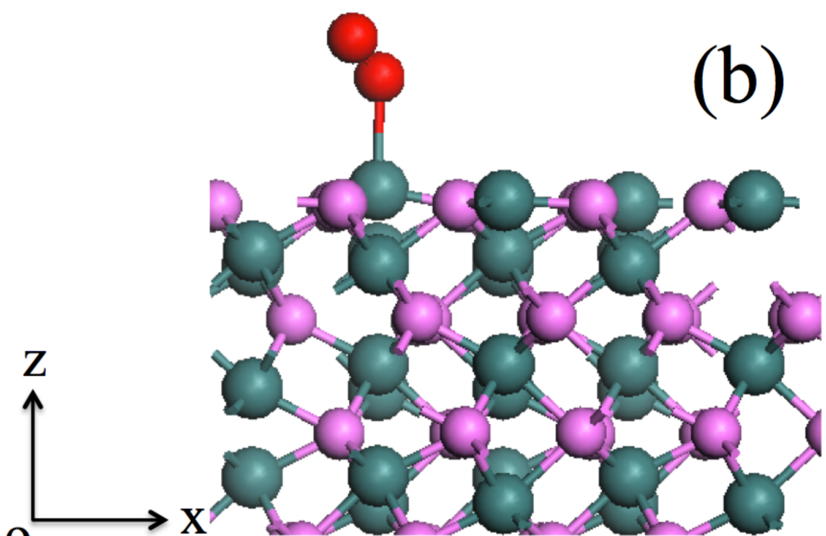
Density Functional Theory (DFT) done with Ruqian Wu, Hui Wang, and Jun Hu (UC Irvine)



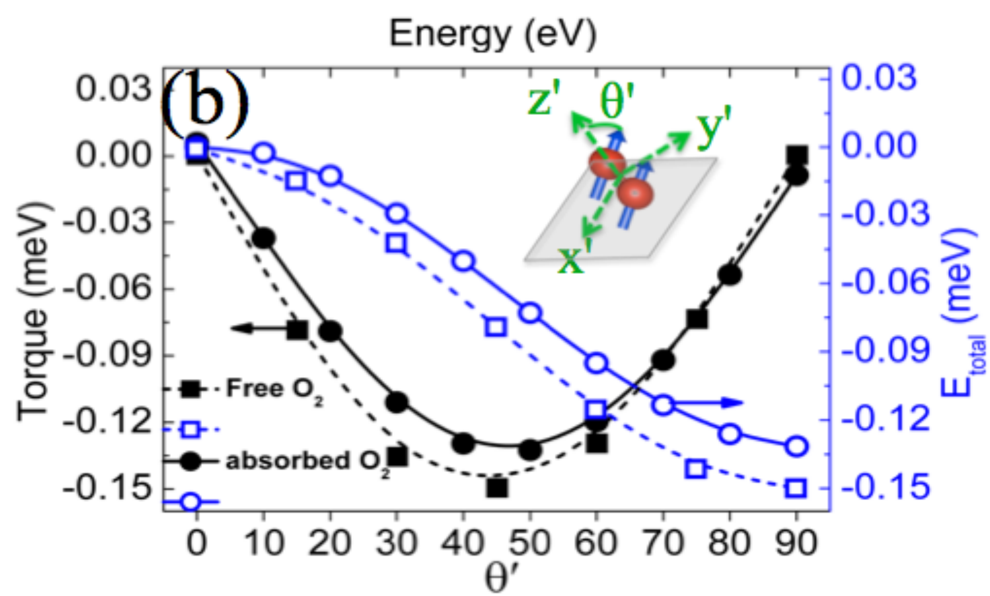
Low barrier for O_2 magnetic moment spin reorientation

- Magnetic moment perpendicular to chemical bond.
- Low barrier (~10 mK) for oxygen spin reorientation on Al_2O_3.
- Thermal fluctuations of spin could produce flux noise.





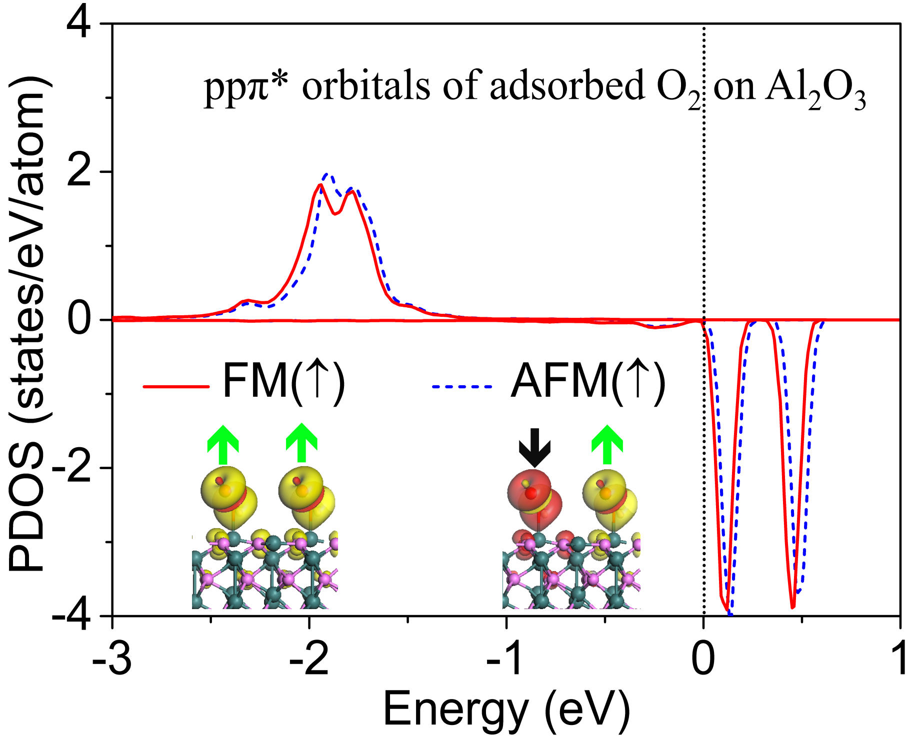
side view



Could spin fluctuations produce 1/f flux (magnetization) noise?

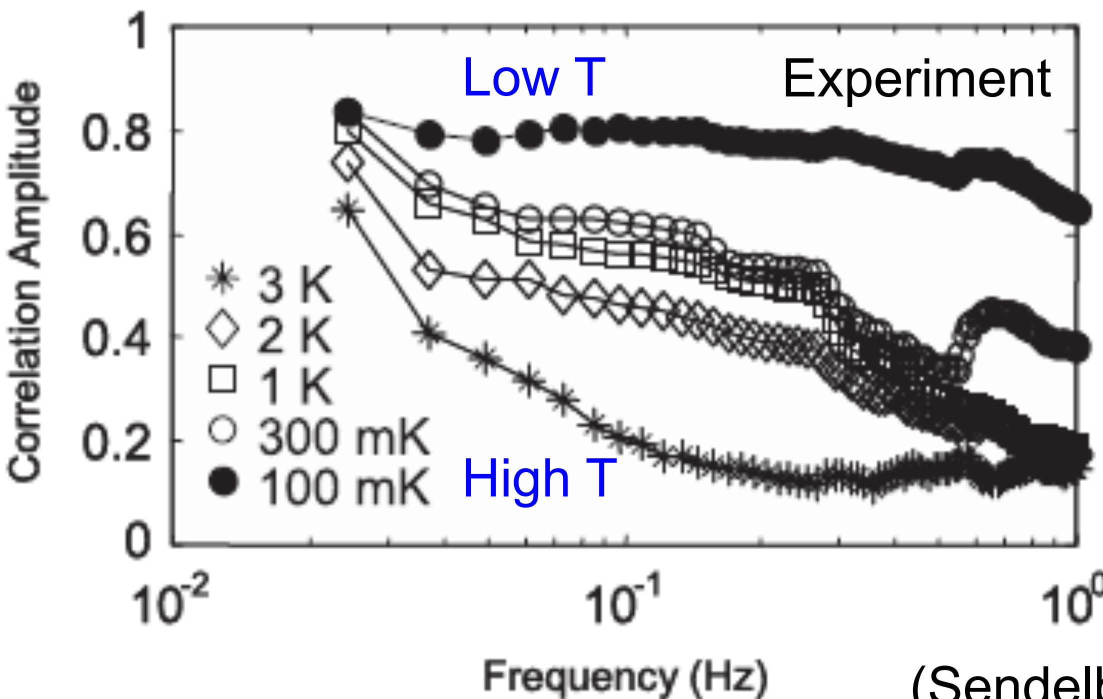
- Need a distribution of spin relaxation times to get 1/f noise.
- Spin interactions would give such a distribution.
- Density functional theory indicates that oxygen molecule spins interact ferromagnetically.

Exchange coupling energy J:
J(r=4.8 Å) = 0.14 meV ~ 1.6 K
J(r=9.6 Å) = 0.05 meV ~ 0.6 K



Fluctuation Cross Correlation Consistent with Ferromagnetism

- Cross correlation $<\delta\Phi\delta L> \sim <\delta M\delta\chi> \sim <(\delta M)^3>$ is odd under time reversal. ($\Phi = LI \leftrightarrow M = \chi H$, $\Phi \leftrightarrow M$, $L \leftrightarrow \chi$, $I \leftrightarrow H$)
- Large cross correlation seen experimentally implies **ferromagnetism** or very slow fluctuators (Weissman).
- Correlation could average to zero over very long times if there is time reversal invariance.

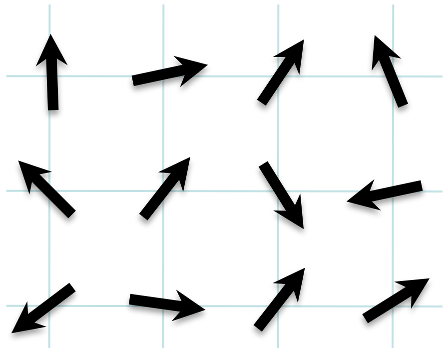


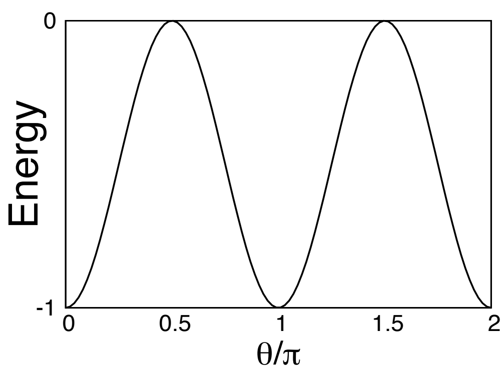
(Sendelbach *et al.* 2009)

Monte Carlo simulations test whether spin fluctuations produce 1/f magnetization noise

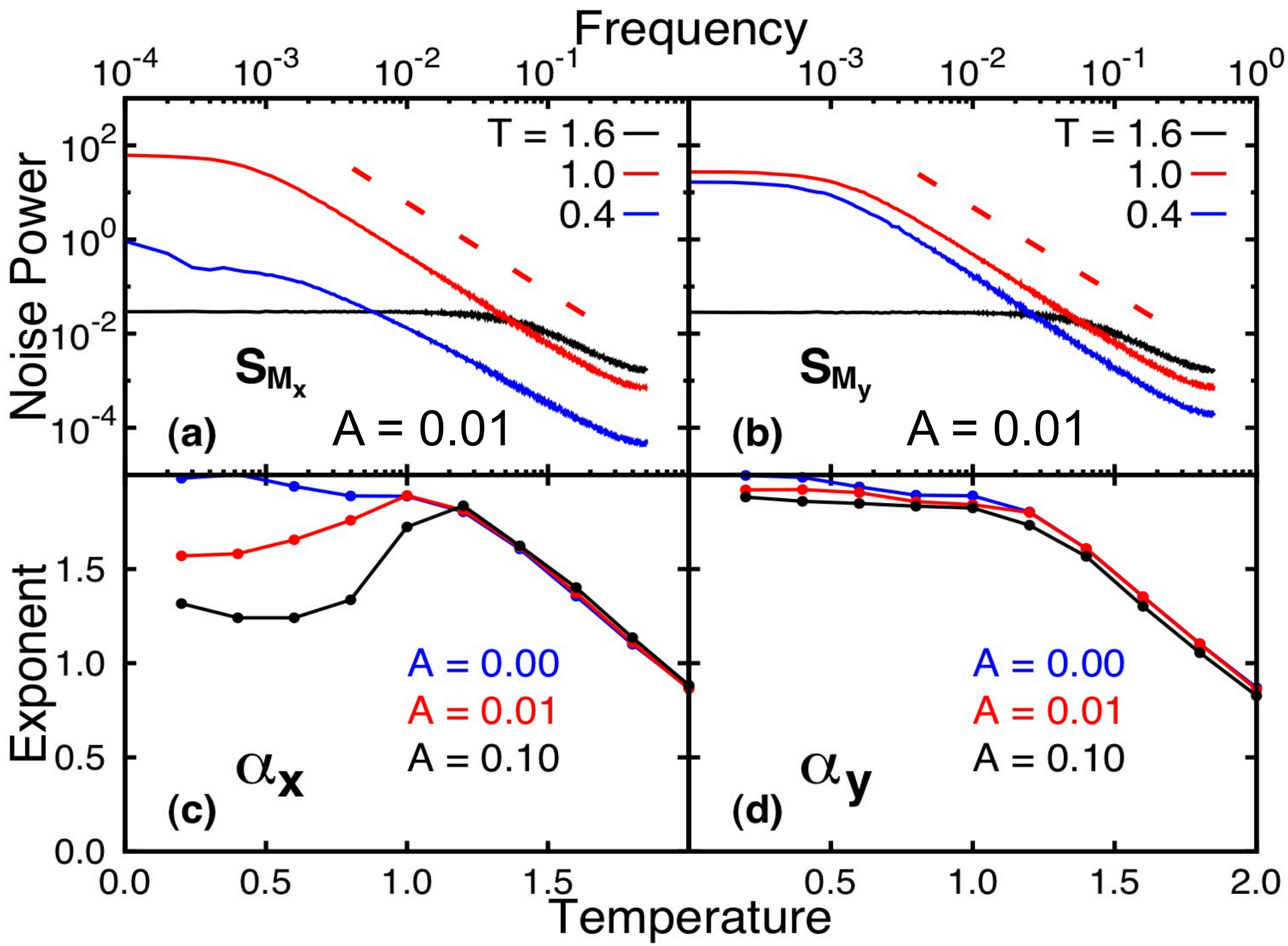
Work done with Chuntai Shi

- We model the adsorbed oxygen molecules as XY spins and investigated whether the combination of in-plane spin anisotropy and ferromagnetic interaction could give rise to the *1/f* type noise spectra.
- The Hamiltonian $$H = -\sum_{\langle i,j \rangle} J_{ij}\left(s_i^x s_j^x + s_i^y s_j^y\right) - A\sum_i \left(s_i^x\right)^2$$
- Poisson-like distribution P(J) of ferromagnetic couplings.
- A = anisotropy energy, i.e., the barrier to spin reorientations
- From DFT, the barrier to spin reorientations is A≈10mK .





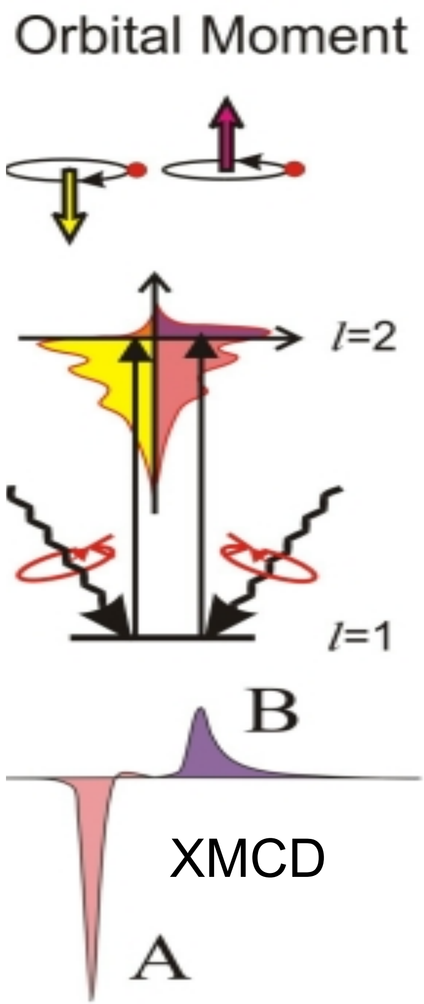
Monte Carlo: O_2 spin fluctuations could produce 1/f flux (magnetization) noise



Work done by Chuntai Shi

Experimental Evidence for Adsorbed Oxygen Molecules Producing a Magnetic Signature and Flux Noise

X-Ray Magnetic Circular Dichroism (XMCD)



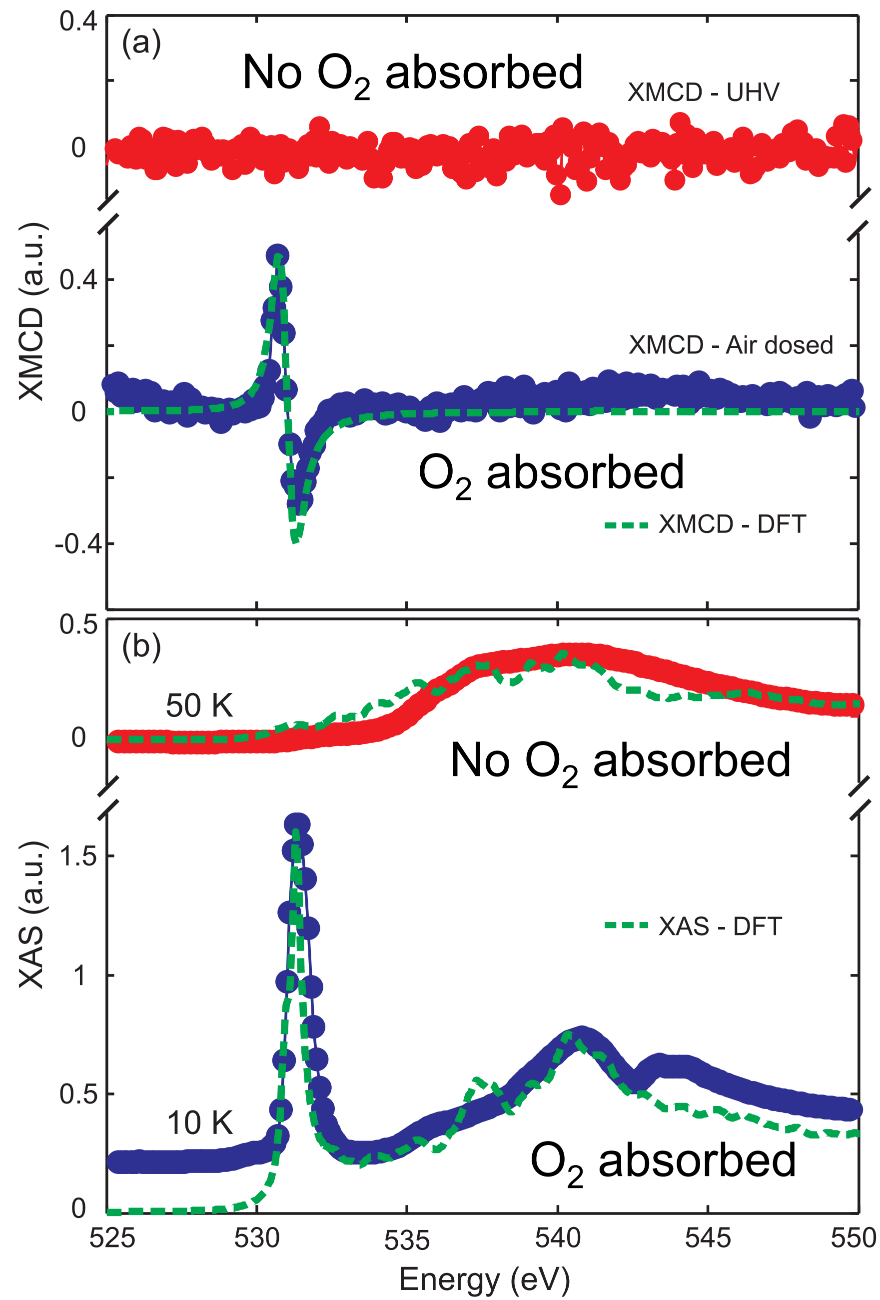
- Magnetic moment couples to orbital angular momentum via spin-orbit coupling.
- Slight imbalance between $Y_{1,1}$ and $Y_{1,-1}$ in $2\pi^*$ in O_2 in B field.
- Detect magnetism by differential absorption of right- (J_z=-ħ) and left- (J_z=+ħ) circularly polarized x-rays which produce transitions from 1s ➔ $2\pi^*$ in O_2. This gives XMCD.
- x-ray absorption spectrum (XAS) is the sum of both polarizations.

https://www-ssrl.slac.stanford.edu/stohr/xmcd.htm

XMCD and XAS

- No XMCD signal on bare Al detected until air was let into chamber and frozen onto Al sample.
- Strength of signal depends on tilt angle of O_2 molecule:
- Best agreement for tilt 55^o from vertical

From Freeland and McDermott groups

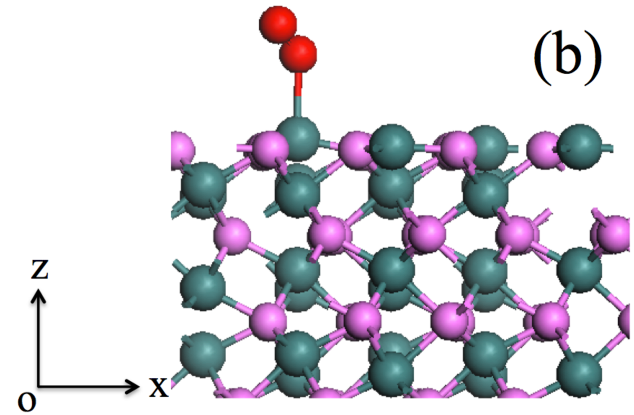


XMCD

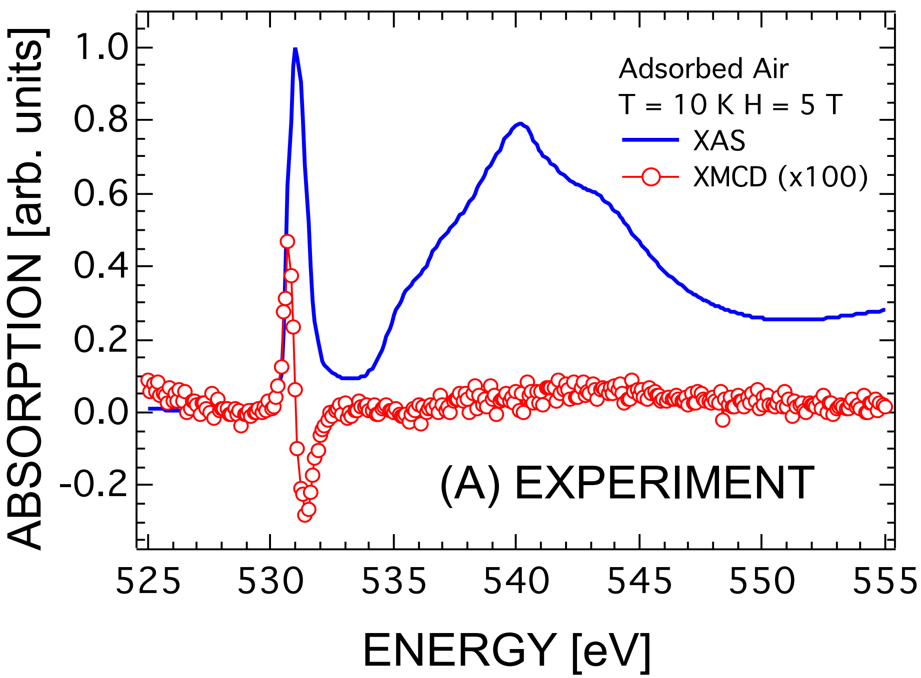
No XMCD signal on bare Al detected until air was let into chamber and frozen onto Al sample.

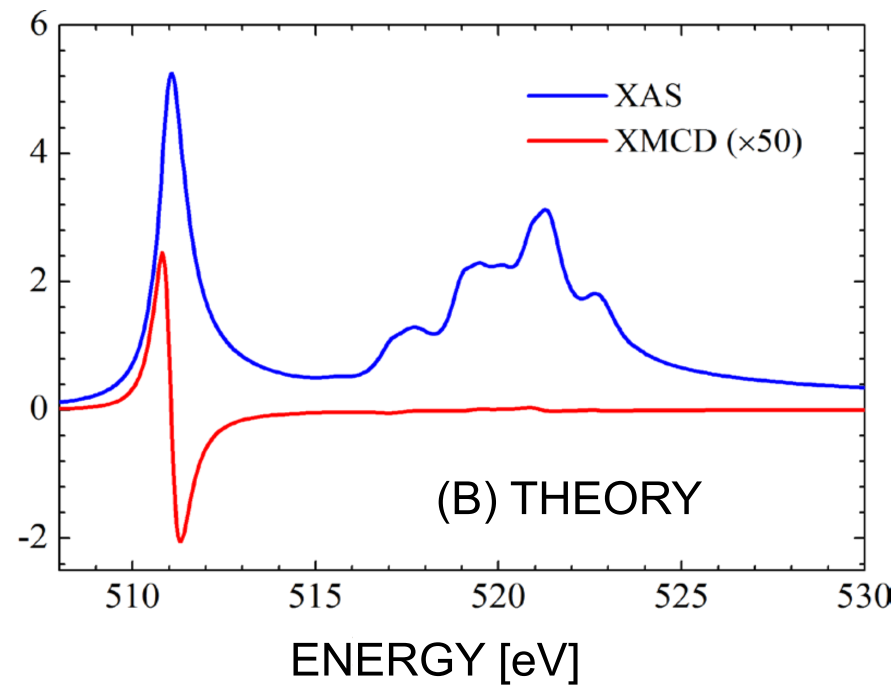
Strength of signal depends on tilt angle of O_2 molecule:

Best agreement for tilt 55° from vertical.



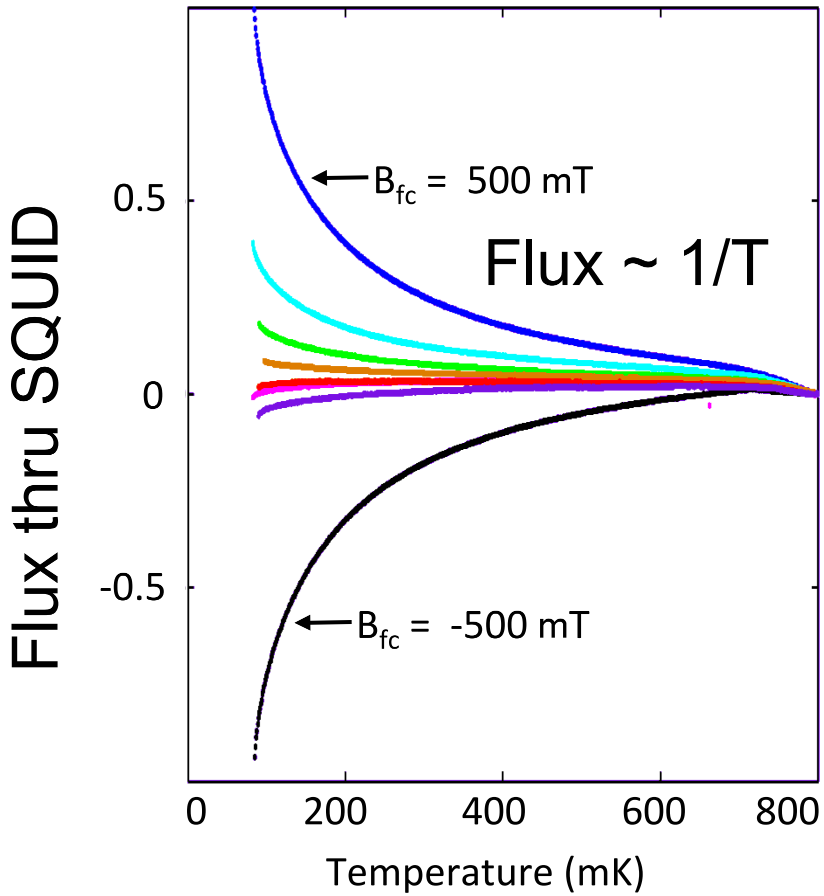
side view





From Freeland and McDermott groups

Recall: Experimental Evidence for Surface Spins

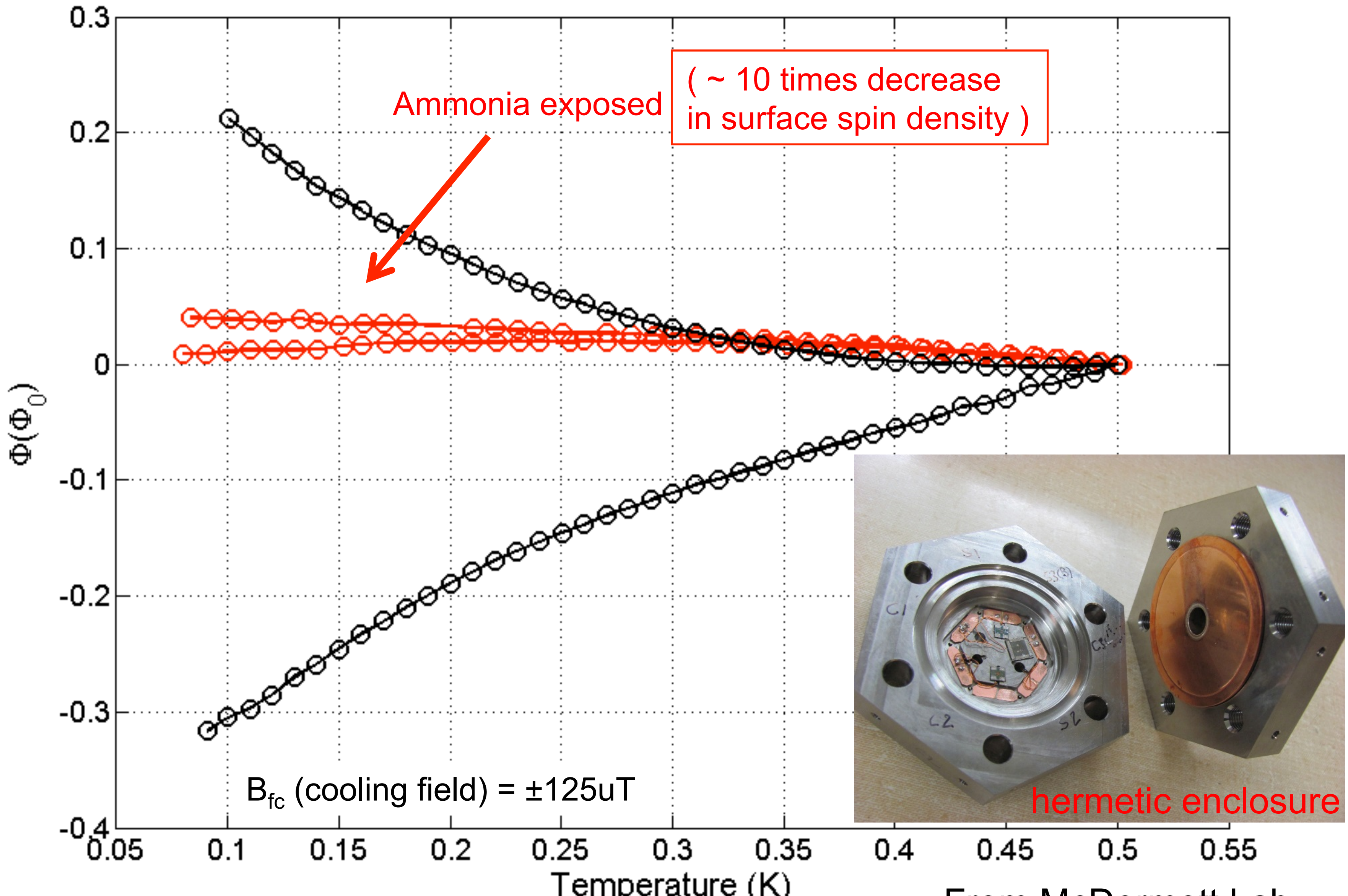


$$\sigma_s \sim 5 \times 10^{17}\,\mathrm{m}^{-2}$$

Surface spin density

[Sendelbach et al., PRL **100**, 227006 (08)]

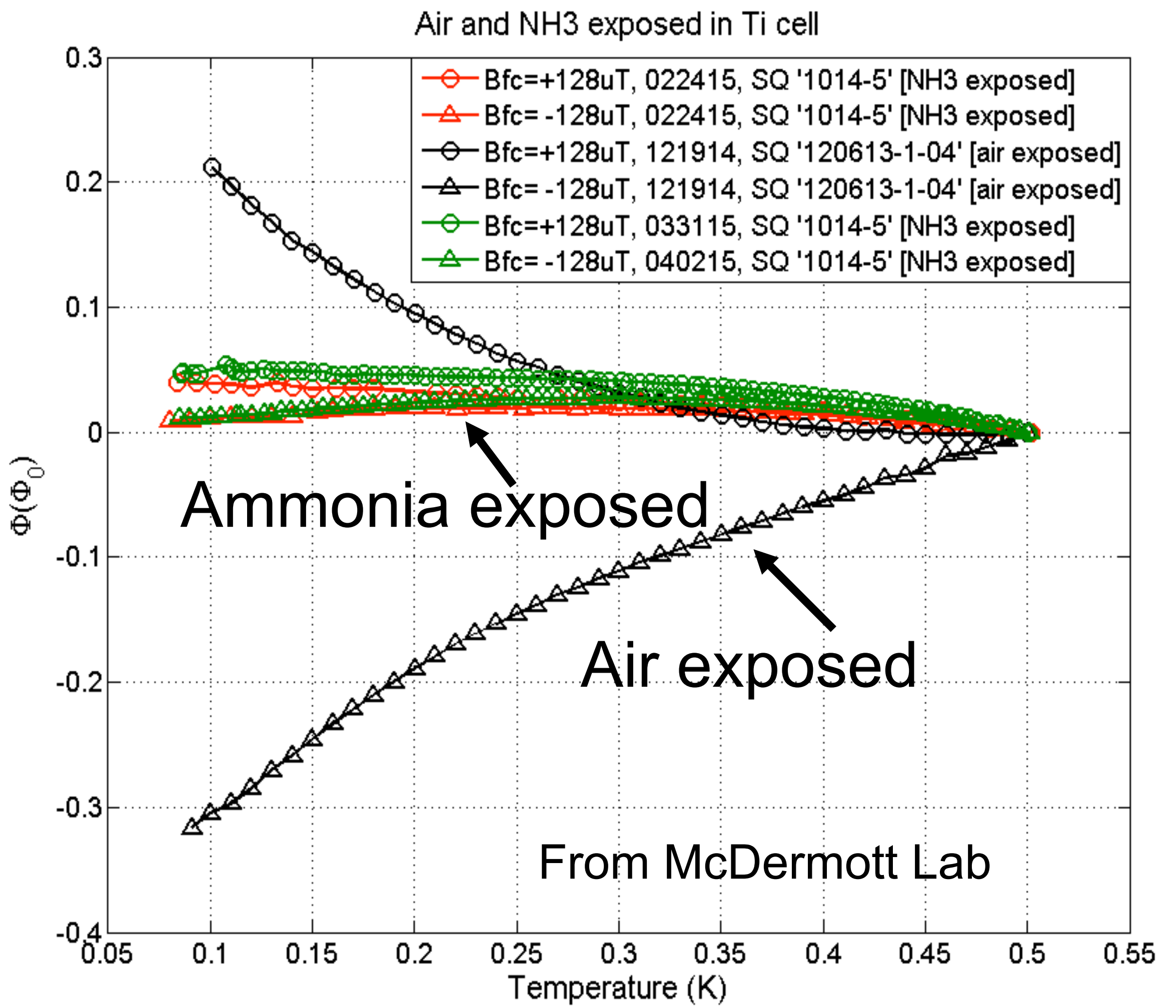
Surface passivation by ammonia in hermetic enclosure reduces flux (susceptibility) in SQUID



From McDermott Lab

Flux (Susceptibility) vs. Temperature

- Flux through Nb SQUID
- Cooling field = 128 μT
- Air: Curie-like 1/T
- NH_3: χ~constant in T
- NH_3 blocks adsorption of O_2
- NH_3 binds 10x more strongly than O_2.
- ~10 times decrease in surface spin density with NH_3



Magnetic susceptibility greatly reduced when sample exposed to ammonia.

Simulations: Decrease in susceptibility should mean decrease in flux noise

- Let M = magnetization per spin
- Susceptibility:

$$\chi = \frac{N\sigma_M^2}{k_B T} \sim \sigma_M^2 \text{ where } \sigma_M^2 \text{ is the variance of M}$$

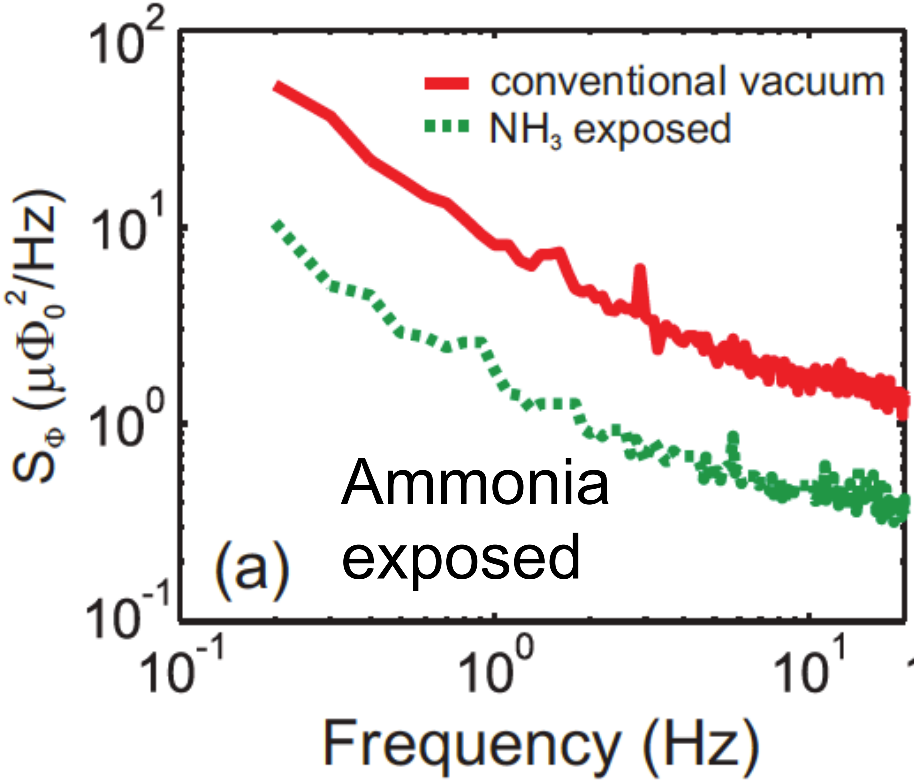
- Total noise power

$$S_{tot} = \frac{1}{N_\tau} \sum_{\omega=0}^{\omega_{\max}} S_M(\omega) = \sigma_M^2$$

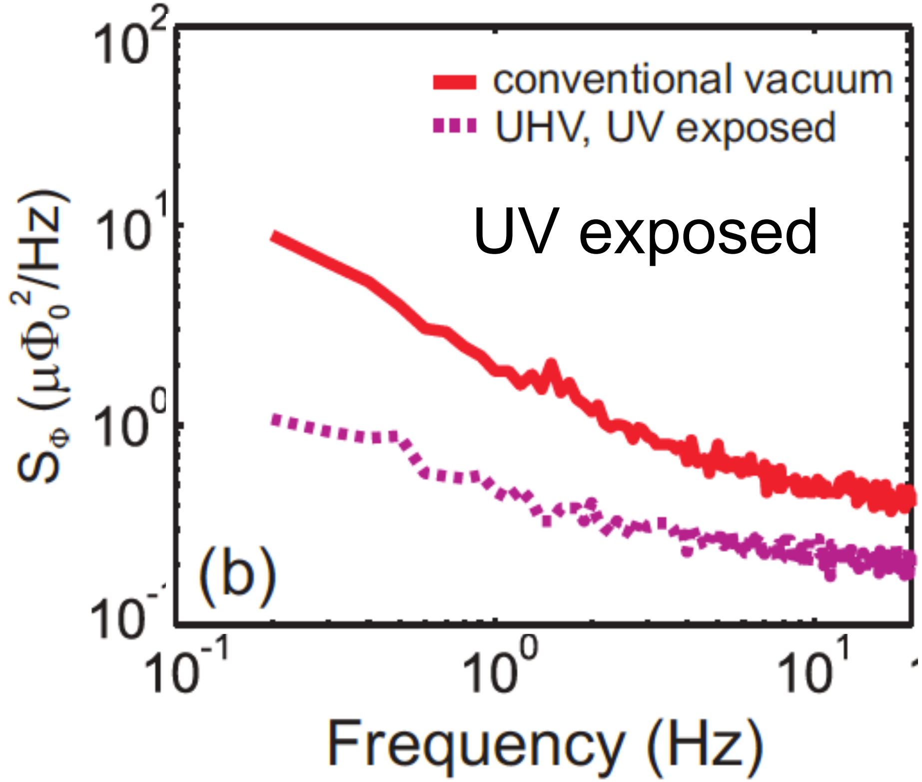
$$\chi \sim \sigma_M^2 \sim S_{tot}$$

Surface Treatments Reduce Flux Noise

Suppression in S_F ~ 5 times



Suppression in S_F ~ 4 times



Flux noise experiments on Al-based SQUIDs encapsulated in SiN_x (P. Kumar and R. McDermott)

Conclusions

- Flux noise in SQUIDs is produced by mysterious magnetic impurities on metal surfaces.
- We propose that paramagnetic O_2 molecules adsorbed on the surface produce flux noise in SQUIDs.
- Evidence for adsorbed O_2 producing magnetic spins (and flux noise) on the SQUID surface
  - Theory: DFT and Monte Carlo simulations.
  - Experiment: Curie-like susceptibility.
  - Experiment: XMCD with and without air exposure.
  - Experiment: Blocking adsorption of O_2 with ammonia significantly reduces the magnetic susceptibility.
  - Experiment: Surface treatments with UHV/UV or ammonia reduce flux noise.

Wang *et al., PRL* **115**, 077002 (2015).

THE END