Defects and Tunneling Systems: Disordered Quantum Solids

Introduction tunneling systems

Tunneling systems in disordered crystals

- thermal properties
- dielectric properties
- interacting TS
- incoherent tunneling

Tunneling systems in amorphous solids

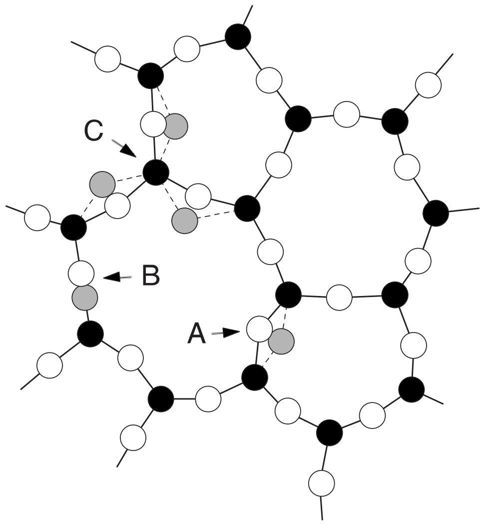
- thermal properties
- dielectric and elastic properties
- spectral diffusion
- experiments on single tunneling systems

Tunneling

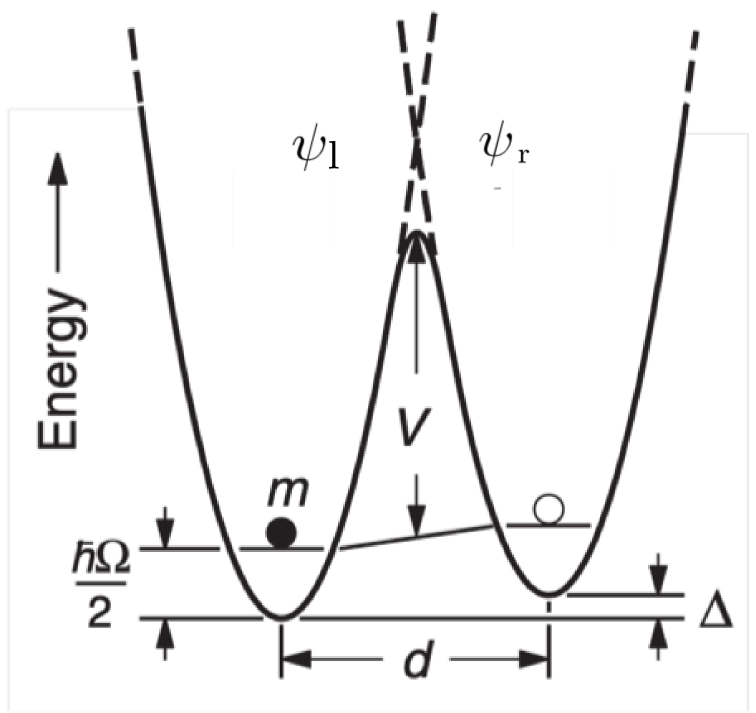
crystal with point defects

amorphous solids

possible structural configurations
with atomic tunneling systems:



double-well potential



typical values: $\Delta / k_B < 10$ K

$d \sim 1$ Å

$\hbar\Omega / k_B \sim 300$ K

$V / k_B < 1000$ K

Atomic Tunneling Systems: two level approximation

total wave function $\psi = a\psi_\mathrm{l} + b\psi_\mathrm{r}$

→ eigenvalue problem: $H\psi = E\psi$

$$E = \frac{\int \psi^* H \psi \,\mathrm{d}^3x}{\int \psi^* \psi \,\mathrm{d}^3x} = \frac{a^2 H_\mathrm{ll} + b^2 H_\mathrm{rr} + 2ab H_\mathrm{lr}}{a^2 + b^2 + 2abS}$$

$$\left\{ \begin{aligned} H_\mathrm{ll} &= \int \psi_\mathrm{l}^* H \psi_\mathrm{l} \,\mathrm{d}^3x \\ H_\mathrm{rr} &= \int \psi_\mathrm{r}^* H \psi_\mathrm{r} \,\mathrm{d}^3x \\ H_\mathrm{lr} &= \int \psi_\mathrm{l}^* H \psi_\mathrm{r} \,\mathrm{d}^3x \\ S &= \int \psi_\mathrm{l}^* \psi_\mathrm{r} \,\mathrm{d}^3x \end{aligned} \right.$$

minimizing *E*: $\partial E/\partial a = 0 \quad \partial E/\partial b = 0$

$$a\,(H_\mathrm{ll} - E) + b(H_\mathrm{lr} - E\,S) = 0$$
$$a\,(H_\mathrm{lr} - E\,S) + b(H_\mathrm{rr} - E) = 0$$

→ $(H_\mathrm{ll} - E)(H_\mathrm{rr} - E) - (H_\mathrm{lr} - E\,S)^2 = 0 \qquad E_\pm = \frac{1}{2}\left(\hbar\Omega \pm \sqrt{\Delta^2 + 4\,H_\mathrm{lr}^2}\right)$

energy zero point $H_\mathrm{ll,rr} = (\hbar\Omega \pm \Delta)/2$

in addition: $S \approx 0$,
overlap is small, *V* is large

$$\boxed{E = E_+ - E_- = \sqrt{\Delta^2 + 4H_\mathrm{lr}^2} = \sqrt{\Delta^2 + \Delta_0^2}}$$

Atomic Tunneling Systems

WKB method

$$-2H_{\mathrm{lr}} = \Delta_0 \approx \hbar\Omega\, \underbrace{\mathrm{e}^{-\lambda}}_{\text{tunneling probability}} \qquad \lambda \approx \frac{d}{2\hbar}\sqrt{2mV}$$

tunneling parameter

isotope effect

- pure tunneling: $E = \Delta_0$
- classical asymmetry energy Δ

Tunneling systems in crystals

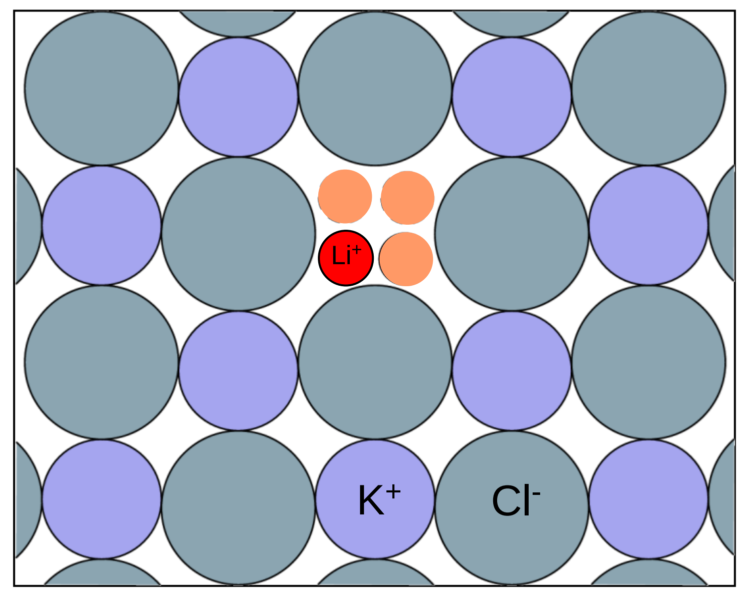
- often more than two minima
- $\Delta \approx 0$

example: KCl:Li

- ▶ Li^+ substitutes K^+
- ▶ ionic radius: $r_{\mathrm{Li}^+} < r_{\mathrm{K}^+}$

⟶ 8 off-center positions in <111> direction

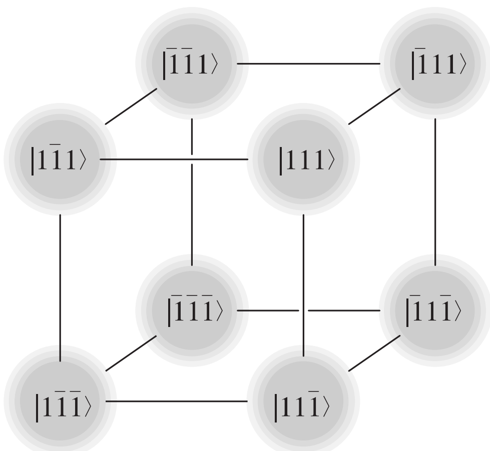
(100)-plane



Tunneling Systems in Crystals

potential minima at $\boldsymbol{r} = \frac{d}{2}(\alpha,\beta,\gamma)$ with $\alpha,\beta,\gamma = \pm 1$

quantum states



$$|\boldsymbol{m}\rangle = \frac{1}{\sqrt{8}} \sum_{\alpha\beta\gamma} \exp\left(\frac{\mathrm{i}\pi}{d}\,\boldsymbol{m}\cdot\boldsymbol{r}\right) |\alpha\beta\gamma\rangle\,,$$

localized states

$$\eta' = \langle 1\,1\,1|\boldsymbol{H}|1\,1\,\bar{1}\rangle = \langle \bar{1}\,1\,1|\boldsymbol{H}|\bar{1}\,\bar{1}\,1\rangle = \ldots$$ edge tunneling

$$\mu' = \langle 1\,1\,1|\boldsymbol{H}|1\,\bar{1}\,\bar{1}\rangle = \langle 1\,\bar{1}\,1|\boldsymbol{H}|1\,1\,\bar{1}\rangle = \ldots$$ face diagonal tunneling

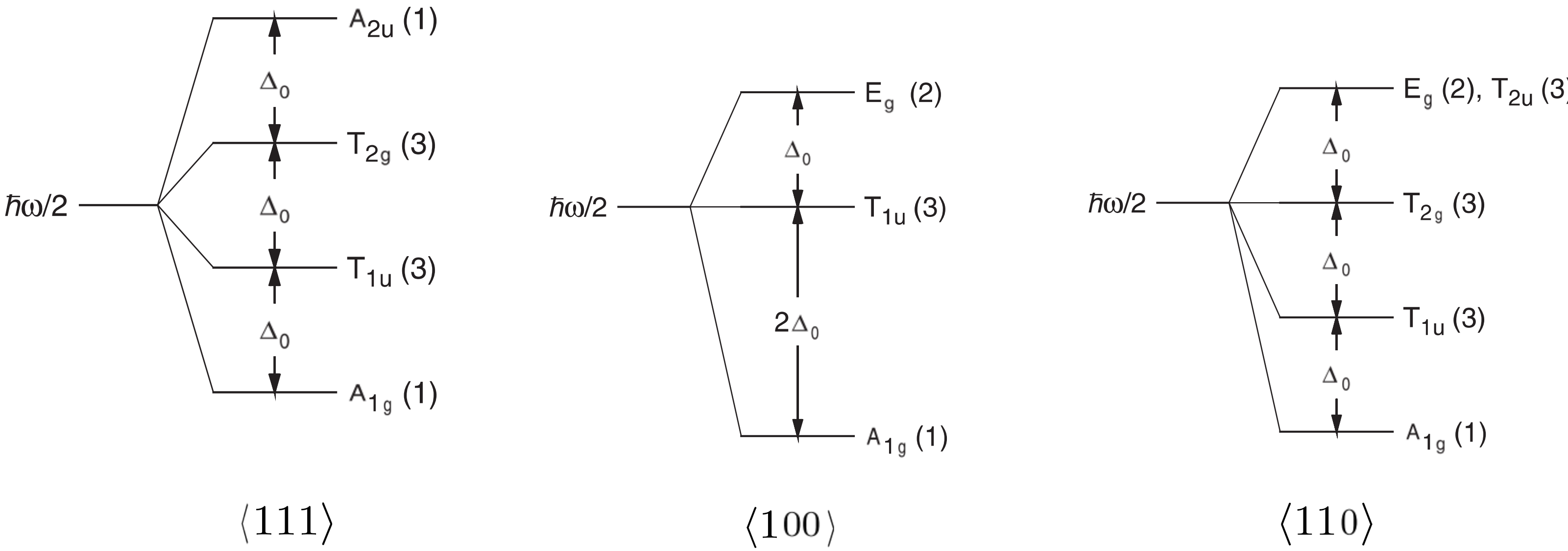
$$\nu' = \langle 1\,1\,1|\boldsymbol{H}|\bar{1}\,\bar{1}\,\bar{1}\rangle = \langle 1\,\bar{1}\,1|\boldsymbol{H}|\bar{1}\,1\,\bar{1}\rangle = \ldots$$ space diagonal tunneling

typically: $\eta' \gg \mu' \gg \nu'$

$$\begin{aligned}
\mathrm{A_{2u}} &: \quad (1,1,1)\,, \\
\mathrm{T_{2g}} &: \quad (1,1,0);(1,0,1);(0,1,1)\,, \\
\mathrm{T_{1u}} &: \quad (1,0,0);(0,1,0);(0,0,1)\,, \\
\mathrm{A_{1g}} &: \quad (0,0,0)\,.
\end{aligned}$$

Tunneling Systems in Crystals

tunneling states with cubic symmetry



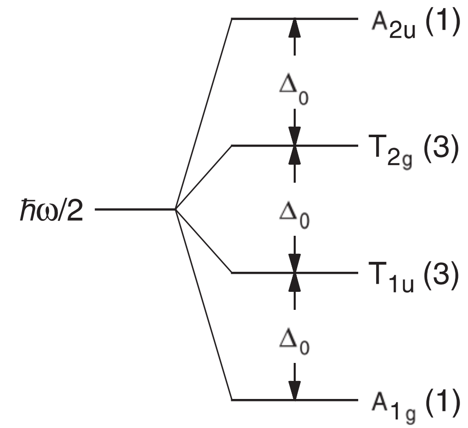
KCl:Li, KBr:C

KCl:OH, LiF:OH

NaBr:F

Tunneling Systems in Crystals

example: $\langle 111 \rangle$ tunneling states



a) partition function

$$Z = \sum_s \mathrm{e}^{-E_s/k_\mathrm{B}T} = 1 + 3\mathrm{e}^{-\Delta_0/k_\mathrm{B}T} + 3\mathrm{e}^{-2\Delta_0/k_\mathrm{B}T} + \mathrm{e}^{-3\Delta_0/k_\mathrm{B}T}$$

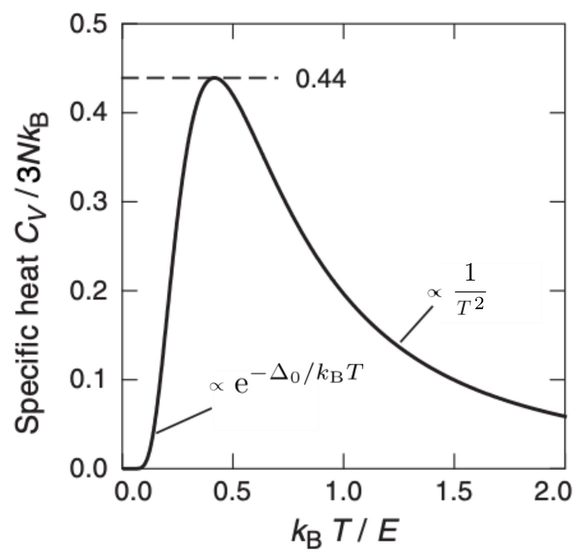
$$= \left(1 + \mathrm{e}^{-\Delta_0/k_\mathrm{B}T}\right)^3$$

b) internal energy

$$U = \frac{N}{Z} \sum_s E_s \mathrm{e}^{-E_s/k_\mathrm{B}T} = 3N\Delta_0 \frac{1}{1 + \mathrm{e}^{\Delta_0/k_\mathrm{B}T}}$$

$$\boxed{U = \frac{3}{2} N\Delta_0 \left[1 - \tanh\left(\frac{\Delta_0}{2k_\mathrm{B}T}\right)\right]}$$

Schottky peak



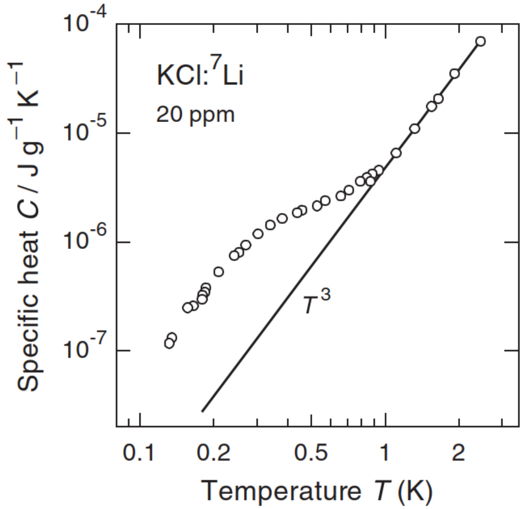
c) specific heat

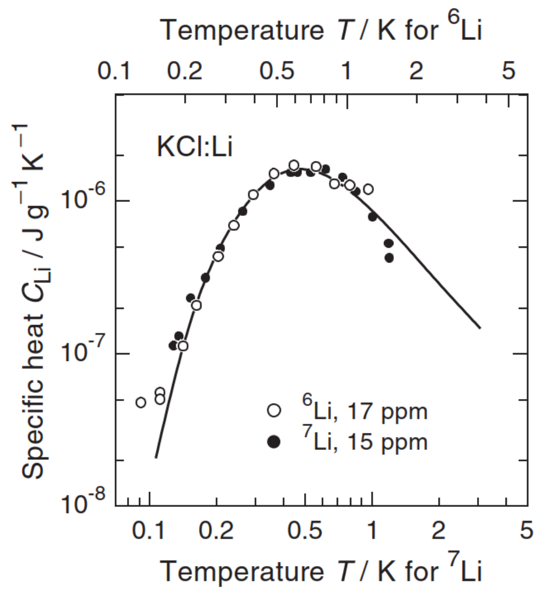
$$C_\mathrm{TS} = \frac{3nk_\mathrm{B}}{\varrho} \left(\frac{\Delta_0}{2k_\mathrm{B}T}\right)^2 \mathrm{sech}^2\left(\frac{\Delta_0}{2k_\mathrm{B}T}\right)$$

Tunneling Systems in Crystals

example: KCl: Li

- above 1K T^3 dependence is observed
- below 1 K additional contribution: Schottky peak
- just 20 ppm Li dominates specific heat





- tunneling system contribution to specific heat

- isotope effect observed:
- proof of tunneling effect

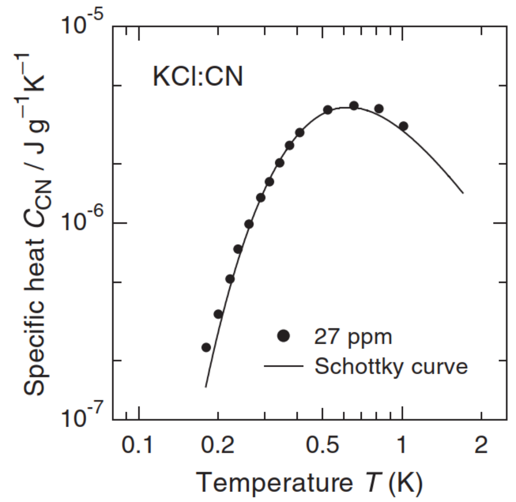
$$^7\Delta_0/k_B = 1.1\,\mathrm{K}$$
$$^6\Delta_0/k_B = 1.65\,\mathrm{K}$$

J.P. Harrison, Phys. Rev. **171**, 1037 (1968)

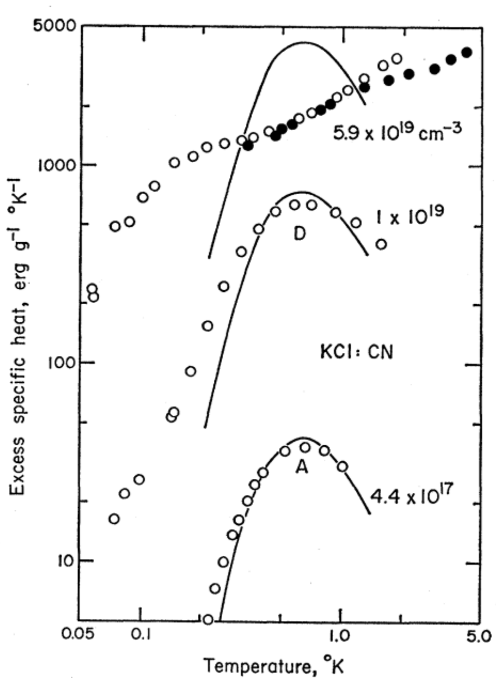
Tunneling Systems in Crystals

example: KCl: CN (same symmetry than KCl:Li)

- T^3 dependence subtracted
- solid line: Schottky peak



- broadening at higher concentrations
- contributions of pairs
- double maximum structure at highest concentration



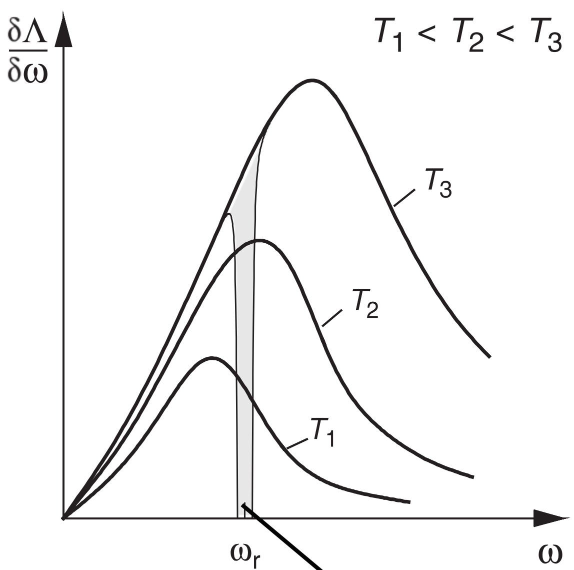
P.P. Peressini, J.P. Harrison, R.O. Pohl,
Phys. Rev. **182**, 939 (1969)

Tunneling Systems in Crystals

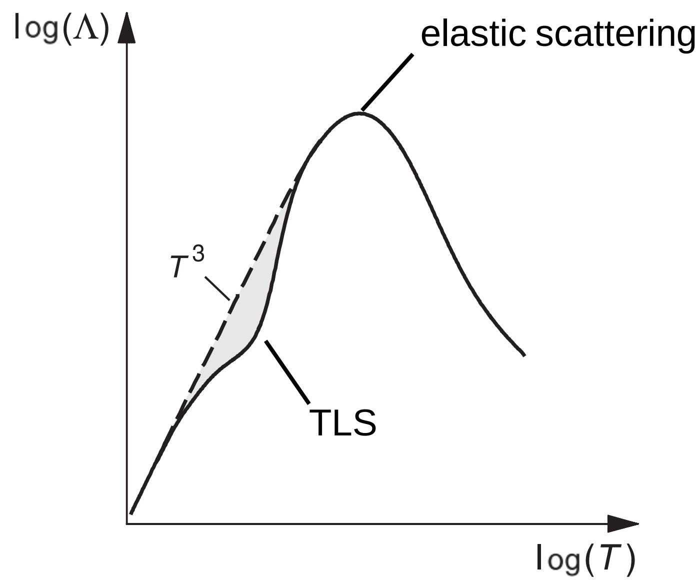
Thermal conductivity:

phonon transport, but resonant absorption via TS

→ hole in differential thermal conductivity

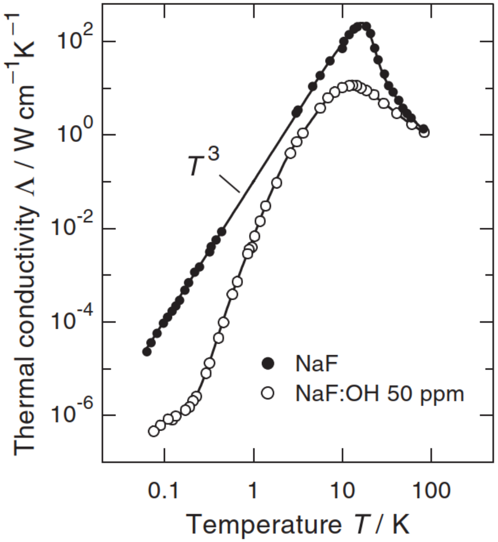


width is determined by coupling of TLS to phonons



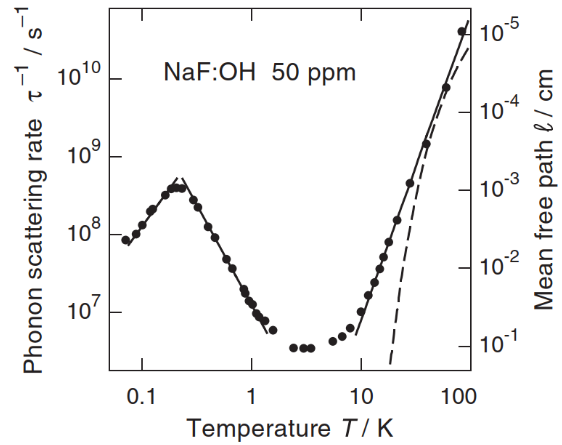
for $\hbar\omega_r \approx k_B T$ reduction of thermal conductivity

Tunneling Systems in Crystals

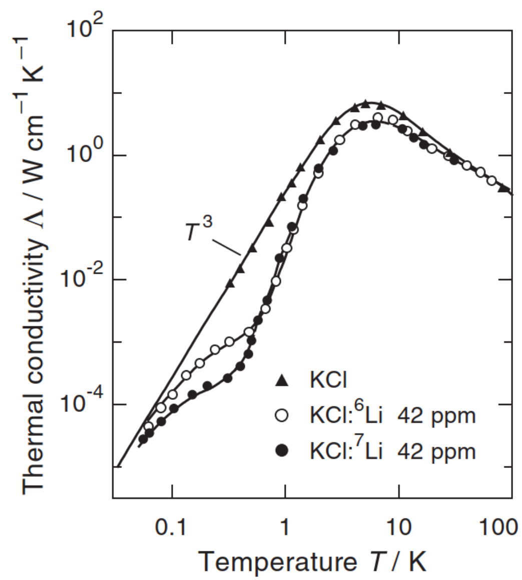


T.F. McNelly, Ph.D. Thesis
(Cornell University 1974)

scattering rate / mean free path



- ▶ strong impact at maximum
- ▶ reduction of thermal conductivity
  ⟶ factor of 500 for 50 ppm OH^{-}



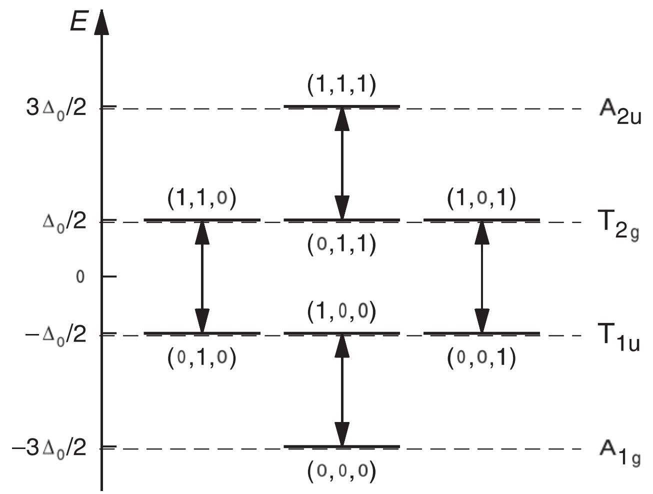
- ▶ isotope effect observed
- ▶ confirms that TS are responsible for heat resistance

P.P. Peressini, J.P. Harrison, R.O. Pohl,
Phys. Rev. 180, 926 (1969)

Tunneling Systems in Crystals

Dielectric susceptibility:

- selection rules
- level scheme
- field dependence



Static dielectric susceptibility

$$\varepsilon = 1 + \chi_\infty + \chi_{\mathrm{TLS}}$$

$$\mathcal{F} = -k_{\mathrm{B}} T \ln Z$$

Helmholtz free energy

$$P = -\frac{1}{V}\frac{\partial \mathcal{F}}{\partial F}$$

$$\boxed{\chi = -\frac{1}{V}\left.\frac{\partial^2 \mathcal{F}}{\partial F^2}\right|_{F=0} = \frac{k_{\mathrm{B}}T}{V}\left.\frac{\partial^2 \ln Z}{\partial F^2}\right|_{F=0}}$$

$$E_{(1,1,1)} = -E_{(0,0,0)} = \Delta_0 + \sqrt{\frac{1}{4}\Delta_0^2 + \frac{1}{3}p^2F^2}\,,$$

$$E_{(0,1,1)} = -E_{(1,0,0)} = \Delta_0 - \sqrt{\frac{1}{4}\Delta_0^2 + \frac{1}{3}p^2F^2}\,,$$

$$E_{(1,0,1)} = E_{(1,1,0)} = -E_{(0,1,0)} = -E_{(0,0,1)} = \sqrt{\frac{1}{4}{\Delta_0}^2 + \frac{1}{3}p^2F^2}$$

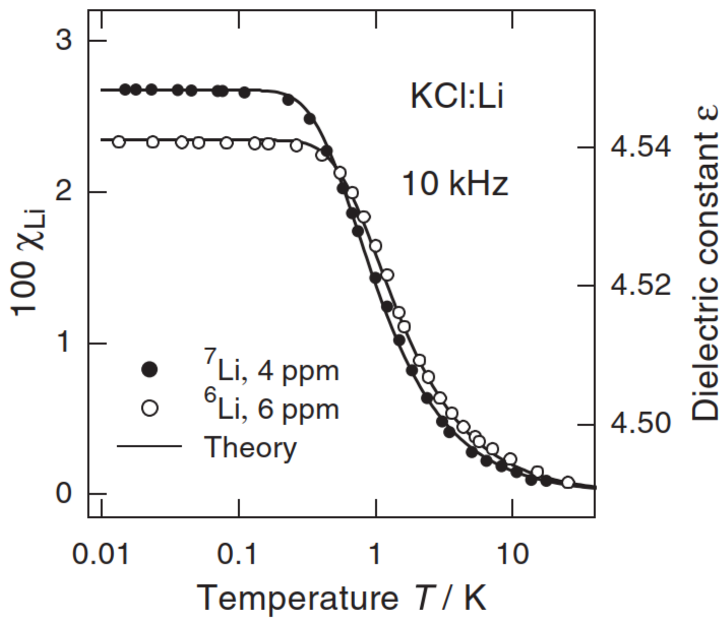
partition function in electric field

$$Z = 4\cosh\left(\frac{1}{k_{\mathrm{B}}T}\sqrt{\frac{1}{4}\Delta_0^2 + \frac{1}{3}p^2F^2}\right)\left(1 + \cosh\left(\frac{\Delta_0}{k_{\mathrm{B}}T}\right)\right)$$

$$\Rightarrow \quad \boxed{\chi_{\mathrm{iso}} = \frac{2}{3}\,\frac{np^2}{\varepsilon_0 \Delta_0}\tanh\left(\frac{\Delta_0}{2k_{\mathrm{B}}T}\right)}$$

Tunneling Systems in Crystals

$$\chi_{\text{iso}} = \frac{2}{3}\frac{np^2}{\varepsilon_0 \Delta_0}\tanh\left(\frac{\Delta_0}{2k_\text{B}T}\right)$$



- high temperature: classical $1/T$ dependence
- low temperature: quantum mechanical plateau $\propto 1/\Delta_0$
- isotope effect clearly observed
- solid line → theoretical description assuming isolated TS

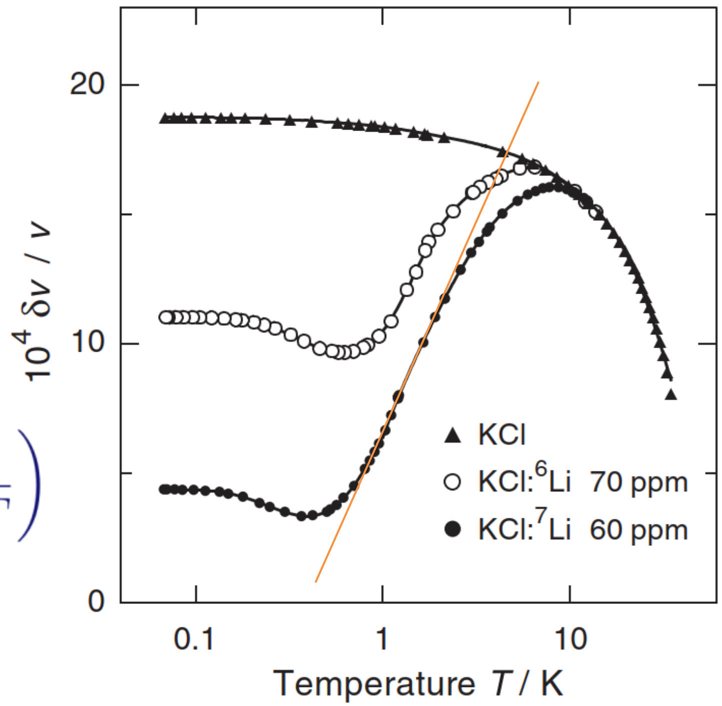
C. Enss, M. Gaukler, S. Hunklinger, M. Tornow, R. Weis, A. Würger, Phys. Rev. B **53**, 12094 (1996)

Tunneling Systems in Crystals

Sound velocity

$$\frac{\delta v}{v} = \frac{-\varrho v^2}{2} s_{44}$$ torsional mode

$$\frac{\delta v}{v} = -\frac{2n\gamma^2}{\varrho v^2 \Delta_0} \tanh\left(\frac{\Delta_0}{2k_\mathrm{B}T}\right) - \frac{n\gamma^2}{\varrho v^2 k_\mathrm{B}T} \mathrm{sech}^2\left(\frac{\Delta_0}{2k_\mathrm{B}T}\right)$$



- high temperature: classical $1/T$ dependence
- low temperature: quantum mechanical plateau $\propto 1/\Delta_0$
- maximum in between: levels contribute that couple linear to strain field

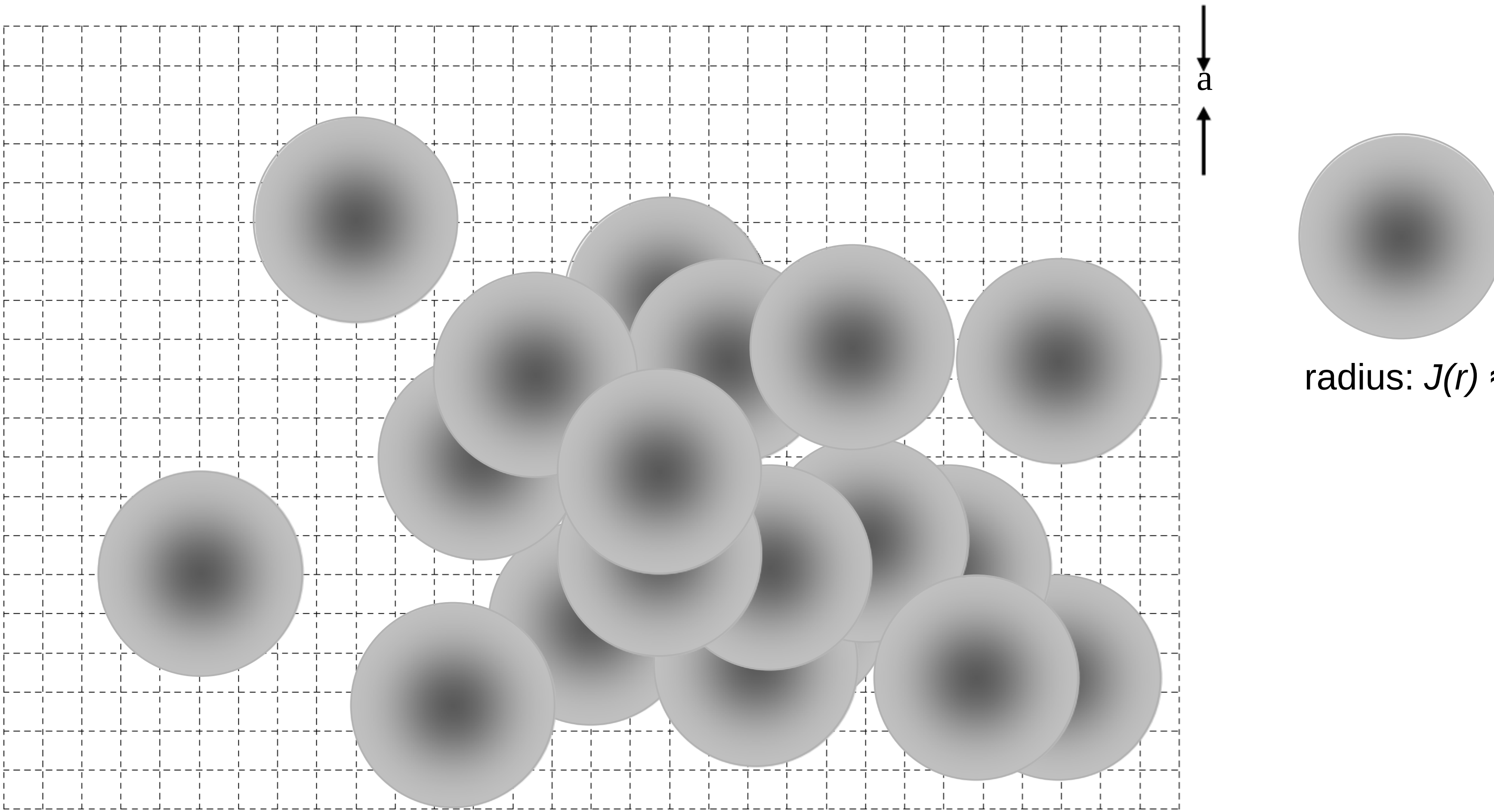
G. Weiss, M. Hübner, C. Enss,
Physica B **263-264**, 388 (1999)

Tunneling Systems in Crystals

Concentration dependence: **example dielectric susceptibility of KCl with TS**

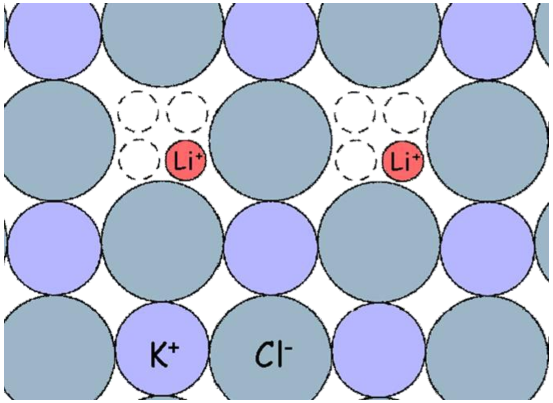
isolate TS ⟶ TS pairs ⟶ many particle interaction

transition to incoherent tunneling



radius: $J(r) \approx \Delta_0$

Tunneling Systems in Crystals



Pair interaction

$$J_{ij} = -\frac{1}{4\pi\varepsilon\ \varepsilon_{\mathrm{KCl}}}\left[\frac{\boldsymbol{p}_i\cdot\boldsymbol{p}_j}{r_{ij}^3} - \frac{3(\boldsymbol{r}_{ij}\cdot\boldsymbol{p}_i)(\boldsymbol{r}_{ij}\cdot\boldsymbol{p}_j)}{r_{ij}^5}\right]$$

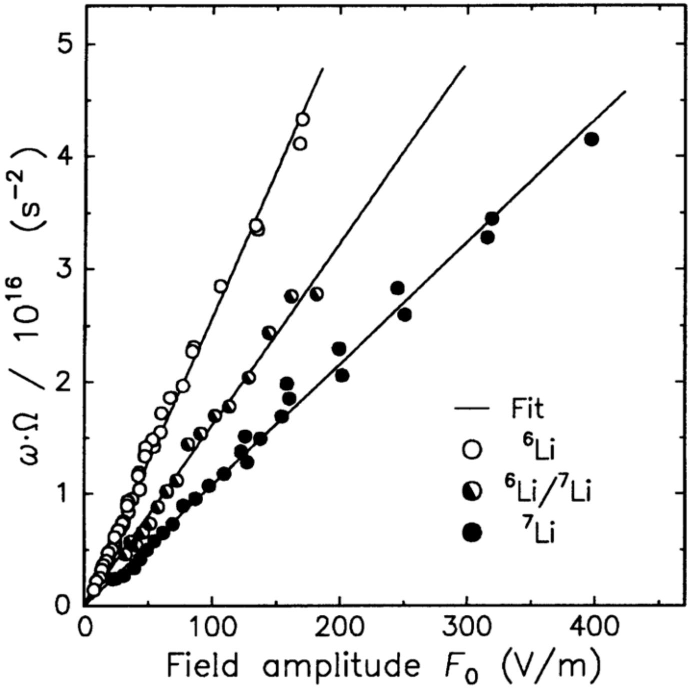
strongly interacting pairs $\longrightarrow$ tunnel as one entity

Rabi frequency (ECHo experiments)

tunnel splitting of pairs

$$\Omega_{\mathrm{R}} = \frac{1}{\hbar}\frac{\Delta_0}{E}\,\boldsymbol{p}\cdot\boldsymbol{F}_0$$

dipole moment of pairs



- KCl with ^{6}Li and ^{7}Li
- observation of mixed pairs
- experimental proof of pair tunneling

R. Weis, C. Enss, B. Leinböck, G. Weiss, S. Hunklinger, Phys. Rev. Lett. **75**, 2220 (1995)

Tunneling Systems in Crystals

↗ $\Delta \neq 0$ widely distributed

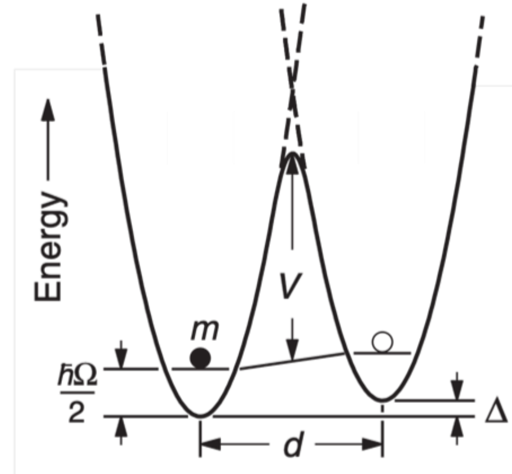
↘ Δ_0 also widely distributed

distribution function $\longrightarrow$ standard tunneling model

$$\boxed{P(\Delta,\lambda)\,\mathrm{d}\Delta\,\mathrm{d}\lambda = P_0\,\mathrm{d}\Delta\,\mathrm{d}\lambda}$$

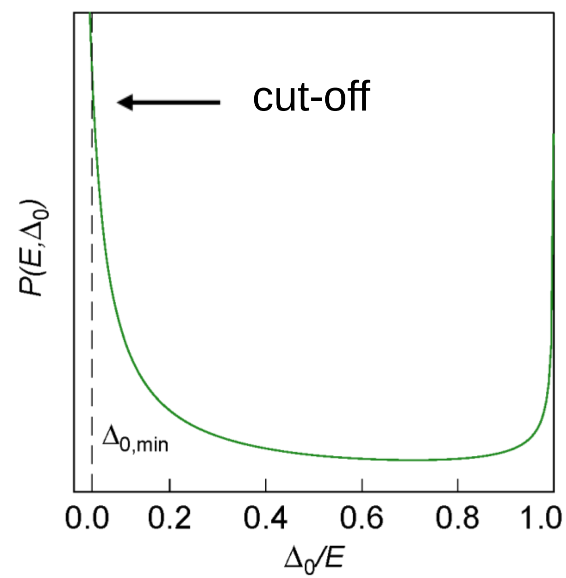
$P(\Delta,\lambda) \longrightarrow P(E,\Delta_0)$ with $E^2 = \Delta^2 + \Delta_0^2$

$$\Delta_0 = \hbar\Omega \mathrm{e}^{-\lambda}$$



$$P(E,\Delta_0)\,\mathrm{d}\Delta_0\,\mathrm{d}E = P(\Delta,\lambda)\left|\frac{\partial\lambda}{\partial\Delta_0}\right|\left|\frac{\partial\Delta}{\partial E}\right|\mathrm{d}\Delta_0\,\mathrm{d}E$$

$$= P_0\,\frac{E}{\Delta_0\sqrt{E^2-\Delta_0^2}}\,\mathrm{d}\Delta_0\,\mathrm{d}E$$



density of states

$$D(E) = \int_{\Delta_0^{\mathrm{min}}}^{E} P(\Delta_0,E)\,\mathrm{d}\Delta_0 = P_0\,\ln\frac{2E}{\Delta_0^{\mathrm{min}}}$$

W.A. Phillips, J. Low. Temp. Phys. **7**, 351 (1972)
P.W. Anderson et al., Philos. Mag. **25**, 1 (1972)

Tunneling Systems in Crystals

Internal energy $D(E) \approx D_0 = \text{const.}$

$$u = \int E\, D(E)\, f(E)\, \mathrm{d}E = D_0 (k_\mathrm{B}T)^2 \underbrace{\int_0^\infty \frac{x}{\mathrm{e}^x + 1}\,\mathrm{d}x}_{\pi^2/12}$$

Fermi-Dirac distribution

$$f(E) = [\exp(E/k_\mathrm{B}T) + 1]^{-1}$$

Specific heat

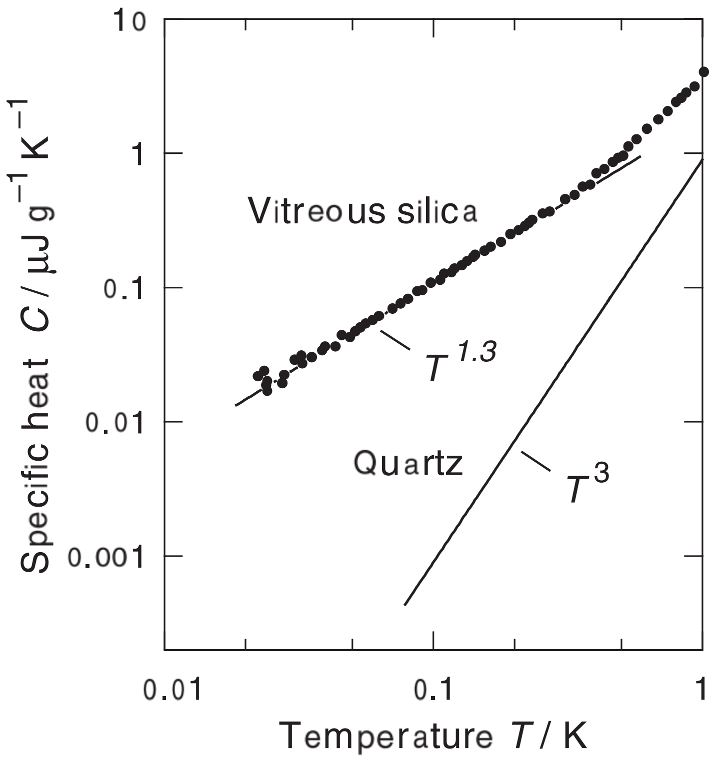
$$C_V = \left(\frac{\partial u}{\partial T}\right)_V = \frac{\pi^2}{6} D_0 k_\mathrm{B}{}^2 T \propto T$$

total specific heat

$$C_V = AT + BT^3 + C_\mathrm{Debye}$$

- additional T^3 term ⟶ quasi-harmonic modes
- linear term $\sim T^{1.3}$ instead of $\sim T$

⟶ good agreement but glass is non-equilibrium system
not all TS can contribute in measuring time



R.C. Zeller, R.O. Pohl,
Phys. Rev. **B 4**, 2029 (1971)

J.C. Lasjaunias et al.,
Sol. State Commun. **17**, 1045 (1975)

Tunneling Systems in Crystals

Heat release

effective density of states

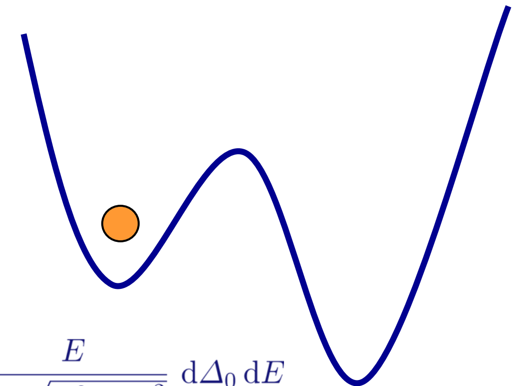
measuring time

$$D_{\mathrm{eff}}(E,t_0) = \int_{\tau_{\min}}^{t_0} P(E,\tau)\,\mathrm{d}\tau = \frac{P_0}{2}\ln\frac{4t_0}{\tau_{\min}}$$

minimum relaxation time

$$P(E,\tau) = \frac{P_0}{2\tau\sqrt{1-\tau_{\min}/\tau}}$$

$$\tau_1 = A\left(\frac{E}{\Delta_0}\right)^2 \frac{1}{E^3}\tanh\left(\frac{E}{2k_\mathrm{B}T}\right)$$



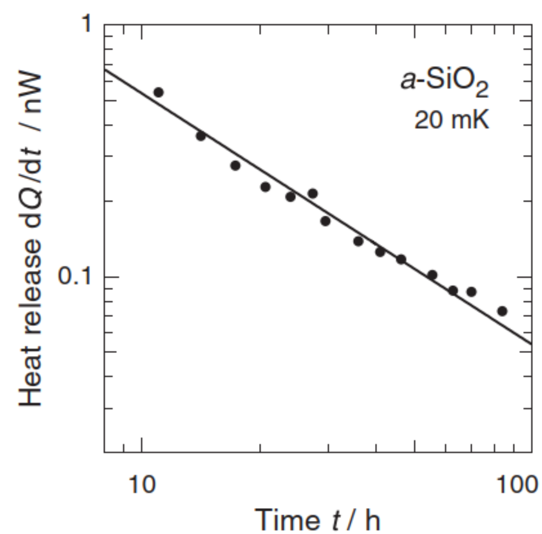
$$= P_0\,\frac{E}{\Delta_0\sqrt{E^2-\Delta_0^2}}\,\mathrm{d}\Delta_0\,\mathrm{d}E$$

➡ $C_V = \dfrac{\pi^2}{12} P_0 {k_\mathrm{B}}^2\, T \ln(4At_0T^3)$

measuring time

➡ heat release of amorphous solids

$$\boxed{\dot{Q} = \frac{\pi^2 k_\mathrm{B}^2}{24} P_0 (T_1^2 - T_0^2)\frac{1}{t}}$$



M. Schwark, M. Kubota, R.M. Mueller, F. Pobell, J. Low Temp. Phys. **58**, 171 (1985)

Tunneling Systems in Crystals

Thermal conductivity

➡ much lower than in crystals

low temperatures: resonant scattering by TLS

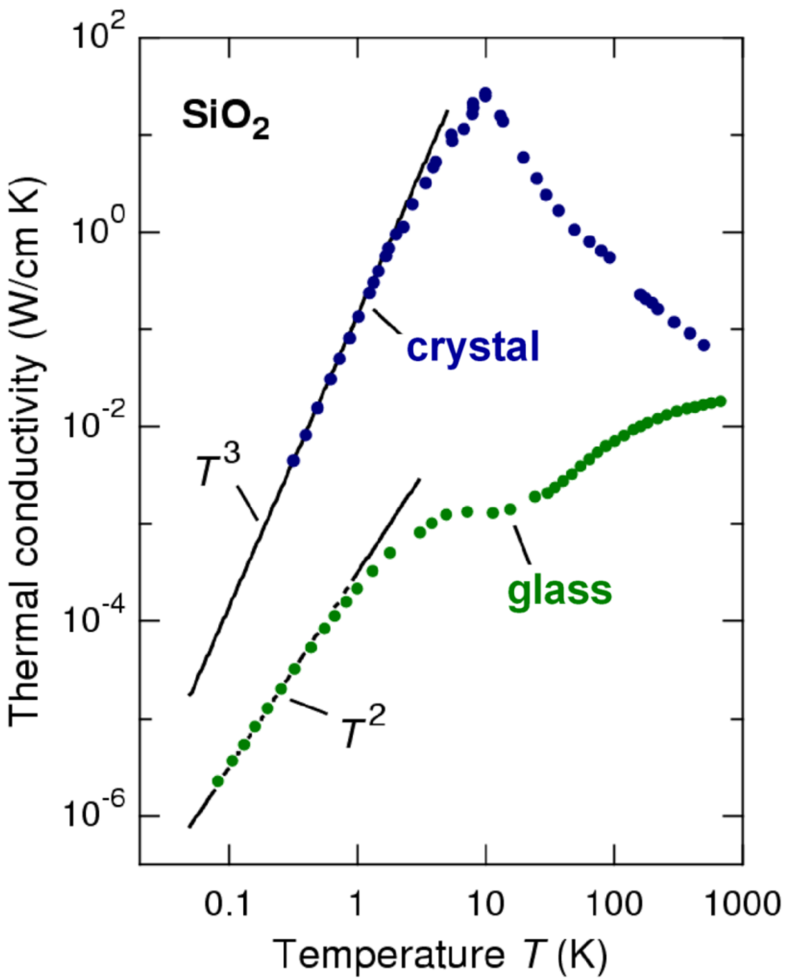
$$\ell^{-1} \propto \omega \tanh\left(\frac{\hbar\omega}{2k_\mathrm{B}T}\right)$$

with dominant phonon approximation:

$\hbar\overline{\omega} \approx k_\mathrm{B}T$ and $\ell^{-1} \propto \overline{\omega} \propto T$

$$\varLambda \propto \underbrace{C_\mathrm{Debye}}_{T^3}\,\underbrace{\ell}_{T^{-1}}$$

➡ $\varLambda \propto T^2$

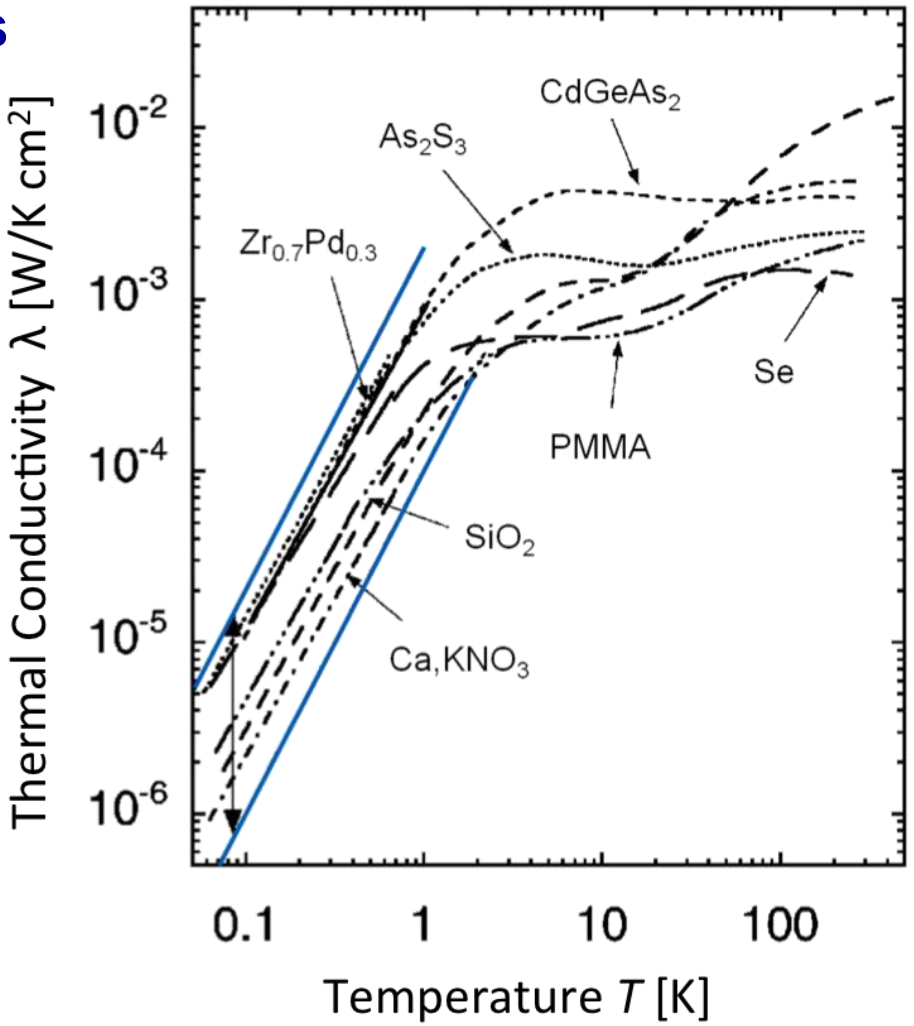


R.C. Zeller, R.O. Pohl, Phys. Rev. **B 4**, 2029 (1971)

Tunneling Systems in Glasses

Universal properties of glasses

➡ Thermal conductivity of glasses within one order of magnitude

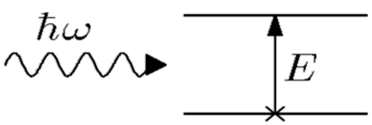


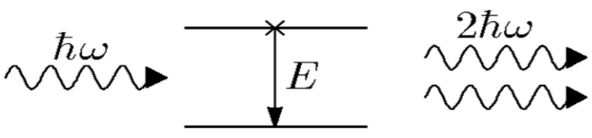
R. B. Stephens, Phys. Rev. B **8**, 2896 (1973)

Tunneling Systems in Glasses

Coupling to Electric and Elastic Fields

resonant processes



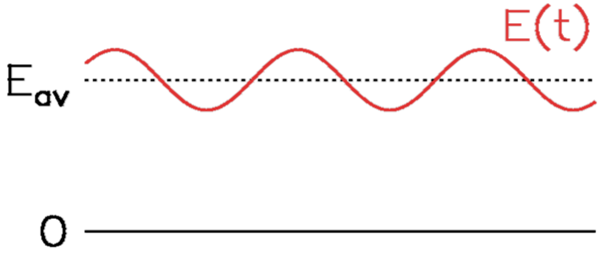


relaxational processes

→ modulation of Δ

$$\delta\Delta = 2\gamma e$$

$$\delta\Delta = 2\,\boldsymbol{p}\cdot\boldsymbol{F}$$

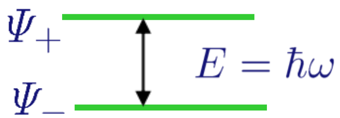


$$\mathcal{H}_S = \frac{1}{E}\begin{pmatrix} \Delta & -\Delta_0 \\ -\Delta_0 & -\Delta \end{pmatrix}(\gamma\,\tilde{e} + \boldsymbol{p}\cdot\boldsymbol{F})$$

Tunneling Systems in Glasses

Echo experiments:

coherent regime: $t \ll \tau_1, \tau_2 \;\rightarrow\; \infty$ two-level approximation:



applied rf field: $F = F_0[\exp(\mathrm{i}\omega t) + \exp(-\mathrm{i}\omega t)] = 2F_0 \cos(\omega t)$

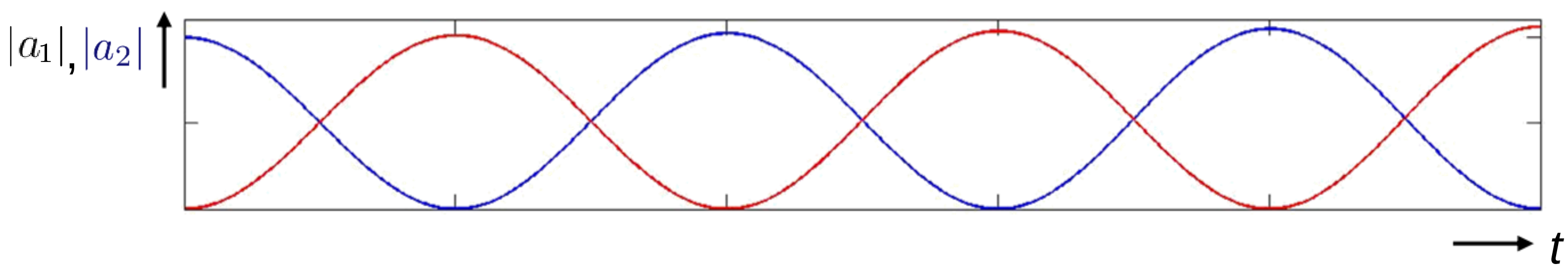
Schrödinger equation: $\mathrm{i}\hbar \dfrac{\partial \Psi}{\partial t} = [H_0 + H_\mathrm{S}]\,\Psi = \left[H_0 + p\dfrac{\Delta_0}{E} F_0\left(\mathrm{e}^{\mathrm{i}\omega t} + \mathrm{e}^{-\mathrm{i}\omega t}\right)\right]\Psi$

Ansatz: $\Psi(t) = a_1(t)\,\Psi_-\,\mathrm{e}^{-\mathrm{i}\omega_1 t} + a_2(t)\Psi_+\mathrm{e}^{-\mathrm{i}\omega_2 t} \longrightarrow \begin{cases} a_1(t) = \cos(\Omega_\mathrm{R} t) \\ a_2(t) = -\mathrm{i}\sin(\Omega_\mathrm{R} t) \end{cases}$

$$\Omega_\mathrm{R} = \frac{1}{\hbar}\frac{\Delta_0}{E}\,\boldsymbol{p}\cdot\boldsymbol{F}_0$$

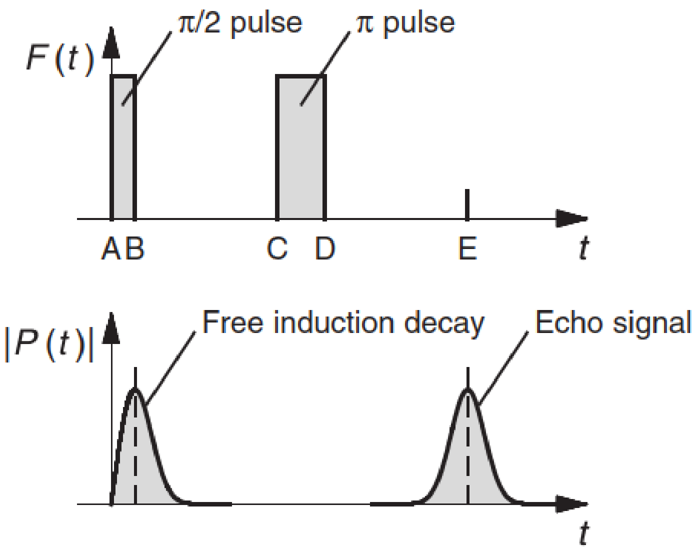
Rabi frequency

occupation number difference varies with Rabi frequency

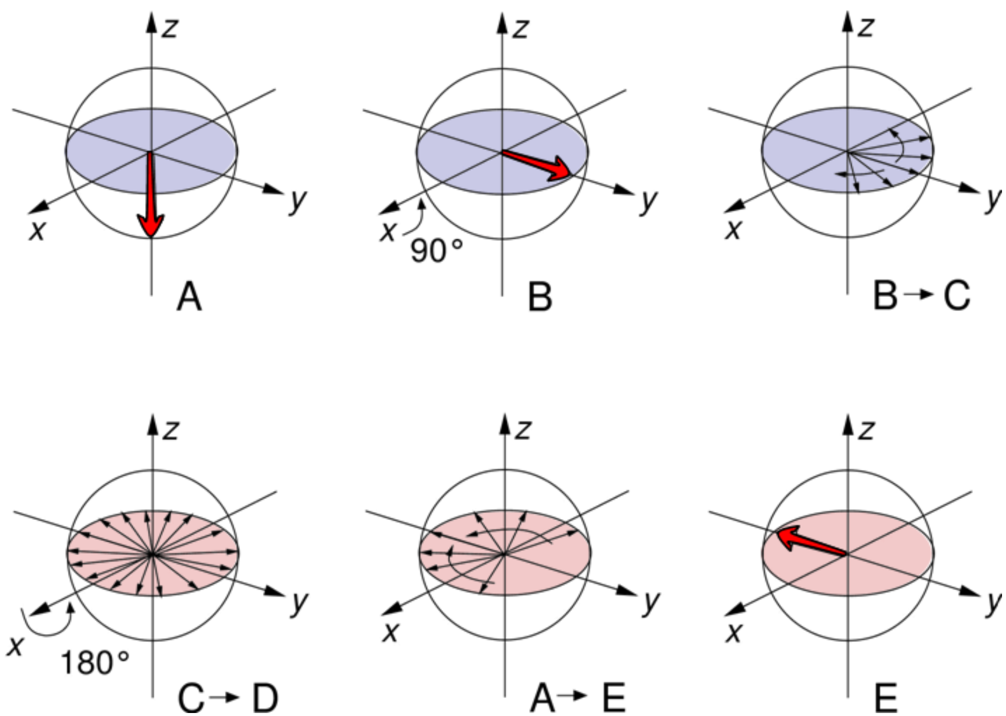


Tunneling Systems in Glasses

Origin of echo

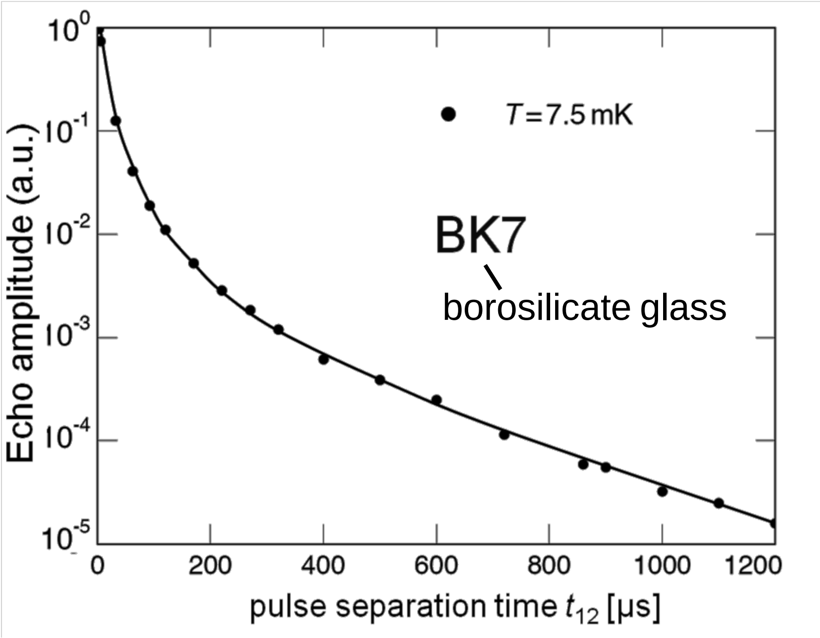


echo generation explained in Bloch sphere



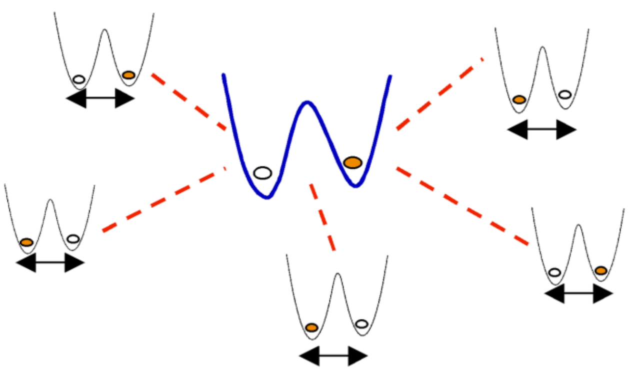
Tunneling Systems in Glasses

two-pulse echo decay

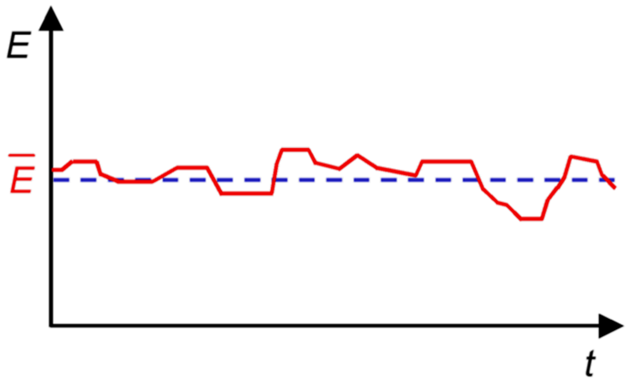


- sensitivity five orders of magnitude
- non-exponential decay

what determines the decay: spectral diffusion



interaction between resonant TS
and thermally fluctuating TS

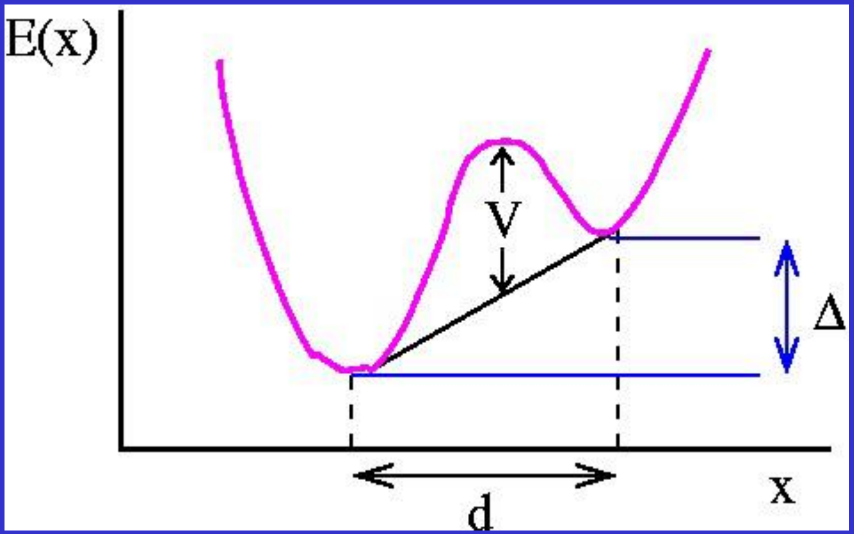


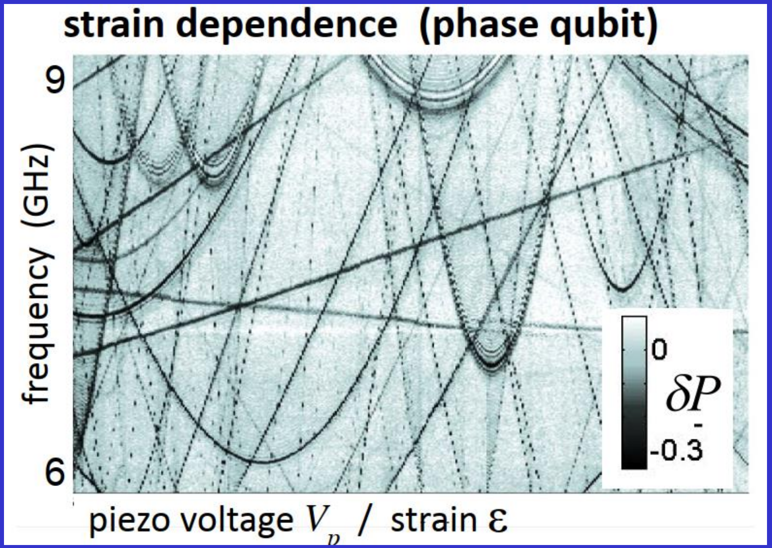
energy splitting of single TS
fluctuating with time

Two Level Systems and 1/f noise

Noise generating two level systems are
– Strain dipoles that couple to the strain field (phonons)
– Electric dipoles (if they are charged) that couple to an electric field (photons)
– Not all TLS have electric dipole moments but all TLS are strain dipoles

TLS systems may cause fluctuations in carrier number, mobility, flux, critical current, dielectric constant, etc.





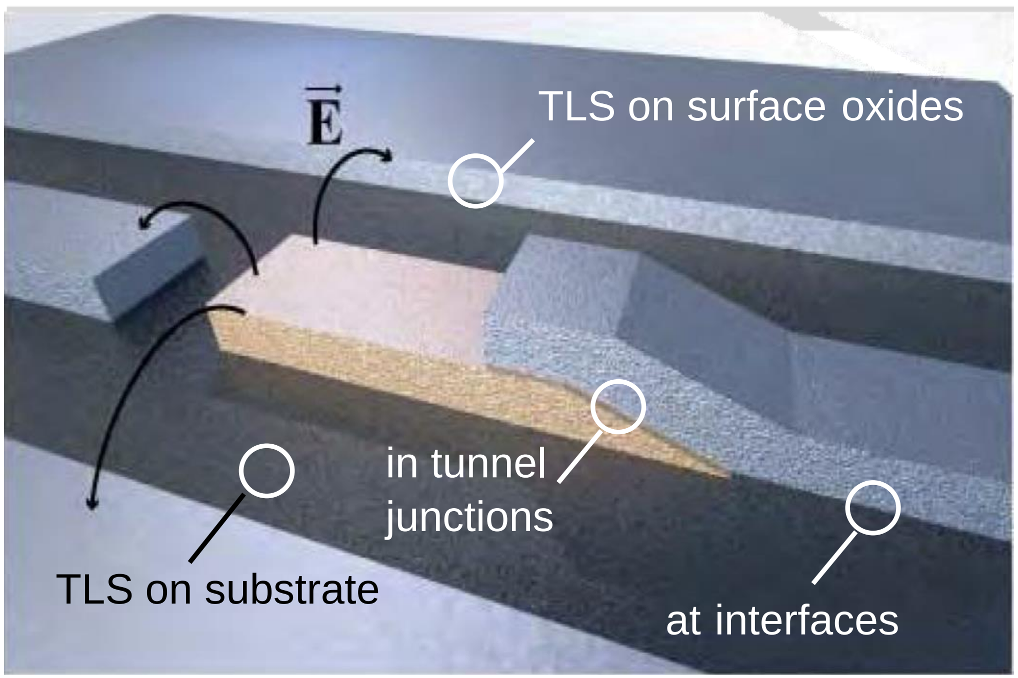
Tunneling Systems in Superconducting Quantum Devices

TLS generate noise & dissipation in

- MOSFETs & single-electron transistors
- micro-mechanical resonators
- single-photon detectors, nanowires
- superconducting resonators and qubits

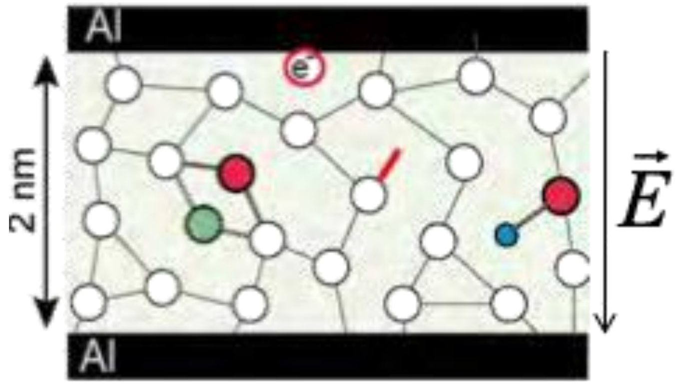
TLS are found

- in surface oxides
- in / on the substrate
- at interfaces
- in tunnel junctions



APL **97**, 252501 (2010) – phase qubit
PRL **95**, 046805 (2005) – charge qubit
PRB **84**, 235102 (2011) – E_J fluctuations

in Josephson junctions:

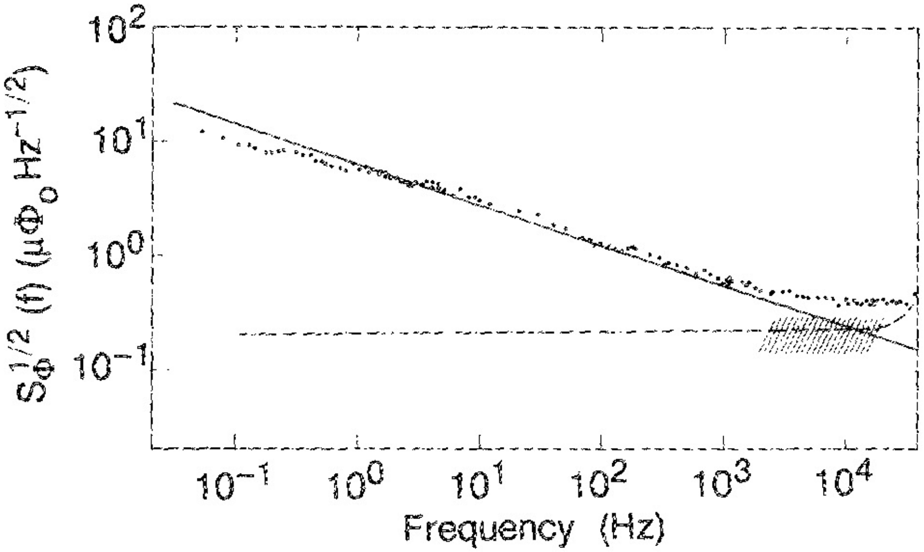


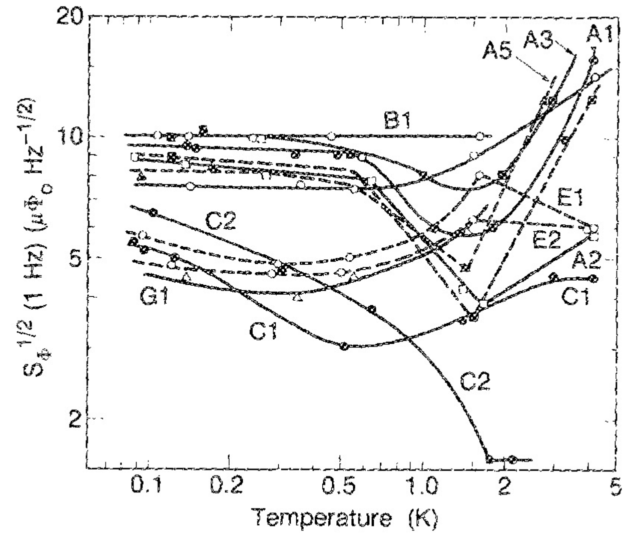
- **hydroxide defects**
- **dangling bonds**
- **electrons trapped at interfaces:**

Kondo- / Andreev Fluctuator

1/f Flux Noise in SQUIDs

$1/f^{\alpha}$ with $0.58 < \alpha < 0.80$ Wellstood *et al.*, APL **50**, 772 (1987)





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

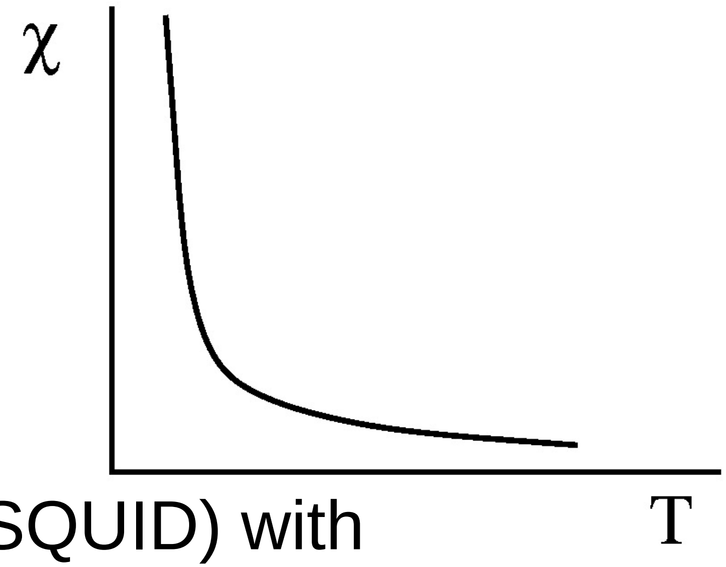
Not due to fluctuating vortices (seen in wires too thin to have a vortex)

Mechanism not fully known

Paramagnetic Susceptibility

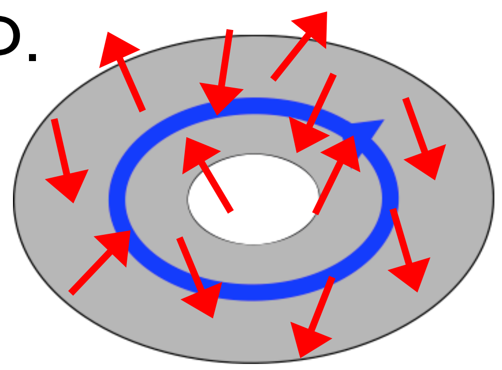
Paramagnetism: Magnetization M is proportional to the magnetic field H

$$M = \chi H$$



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

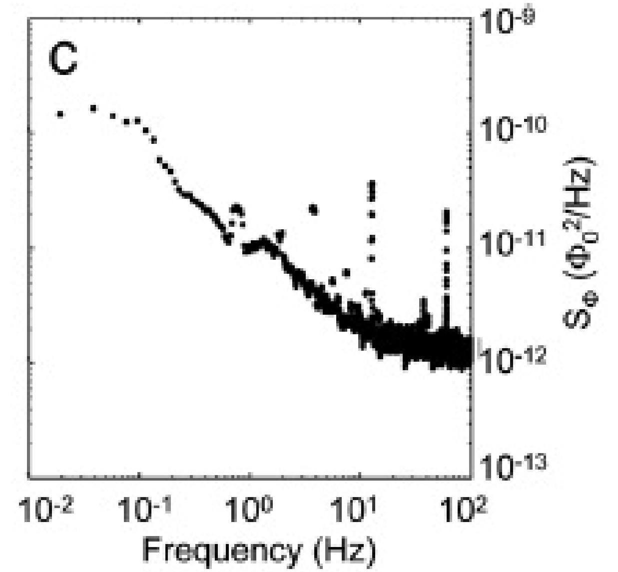
- Consider a toroidal current loop (SQUID) with spins on the surface.
- Current produces B field that polarizes spins.
- Polarized spins contribute to M and flux Φ.
- Flux $\Phi = LI \leftrightarrow$ Magnetization $M = \chi H$.

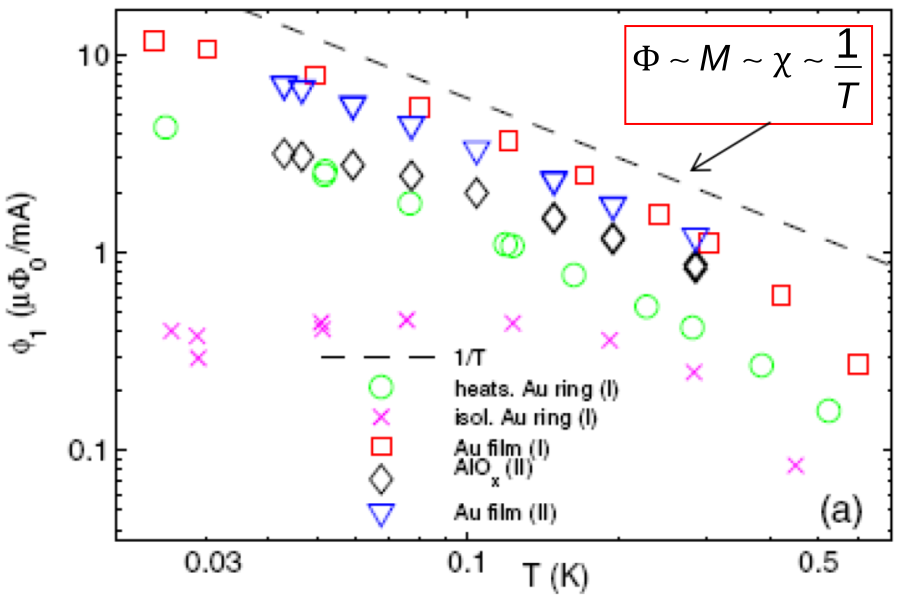


$$\Phi \leftrightarrow M, \quad L \leftrightarrow \chi, \quad I \leftrightarrow H$$

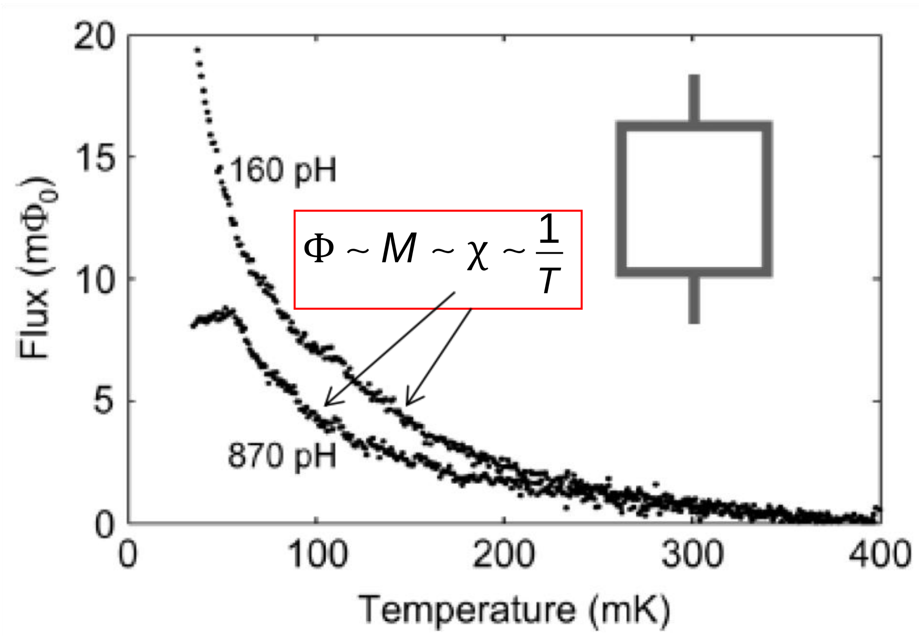
Flux Noise in SQUIDs

- 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.



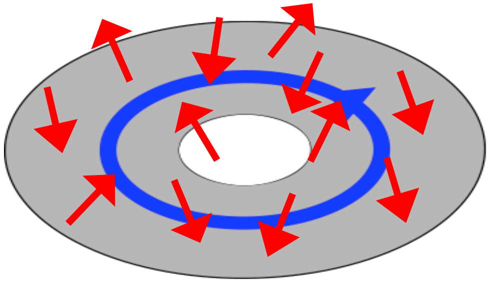


Bluhm *et al. PRL* (2009)



Sendelbach *et al. PRL* (2008)

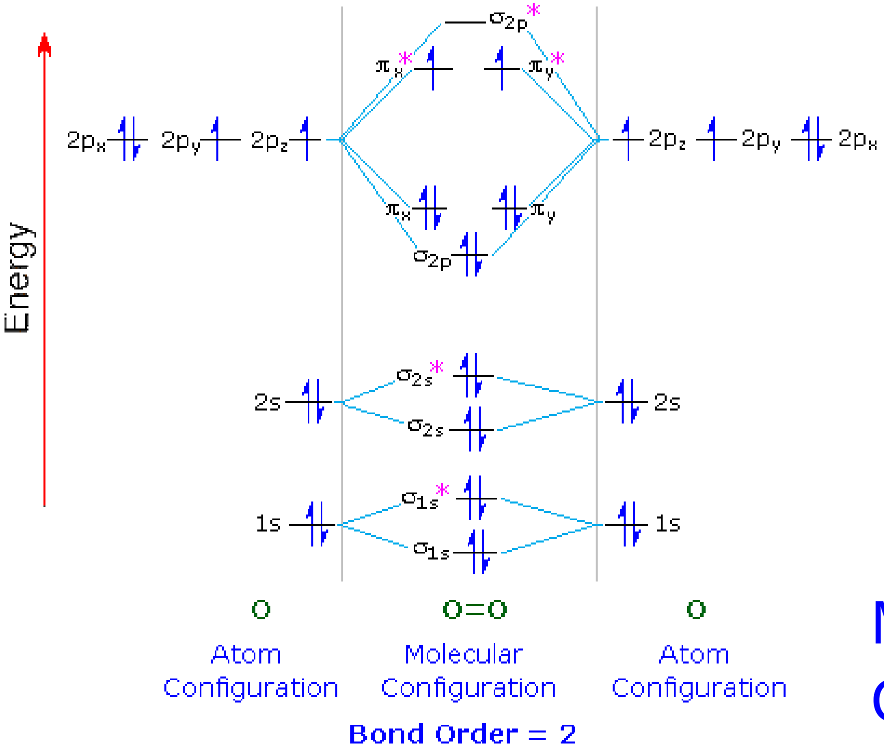
Evidence Indicates Spins Reside on Metal Surface

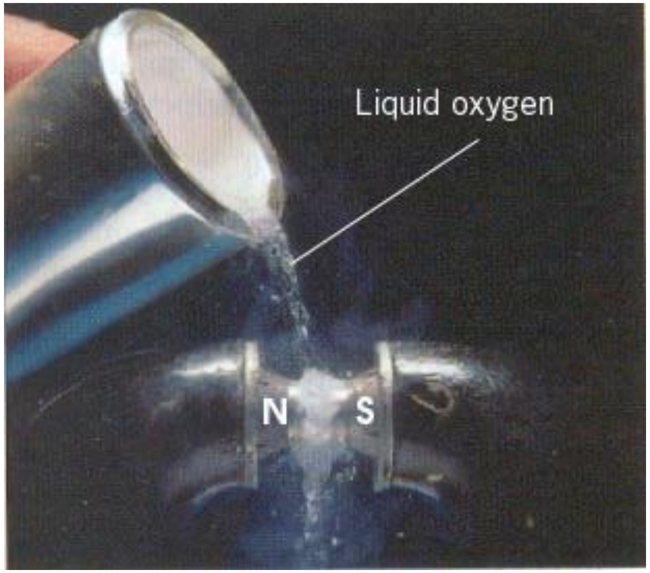


- Flux noise ***scales with surface area of the metal*** in the SQUID.
- Magnetic impurities in the bulk superconductor would be screened.
- Weak localization ***dephasing time τ_φ grows as T decreases*** (Bluhm *et al*.). If spin impurities in the bulk limited τ_φ, τ_φ would saturate at low T (Webb).
- Concentration ~ $5 \times 10^{17}/\mathrm{m}^2$ implies a ***spacing of ~1 nm*** between impurities if spin moment is 1 μ_B.
- 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.

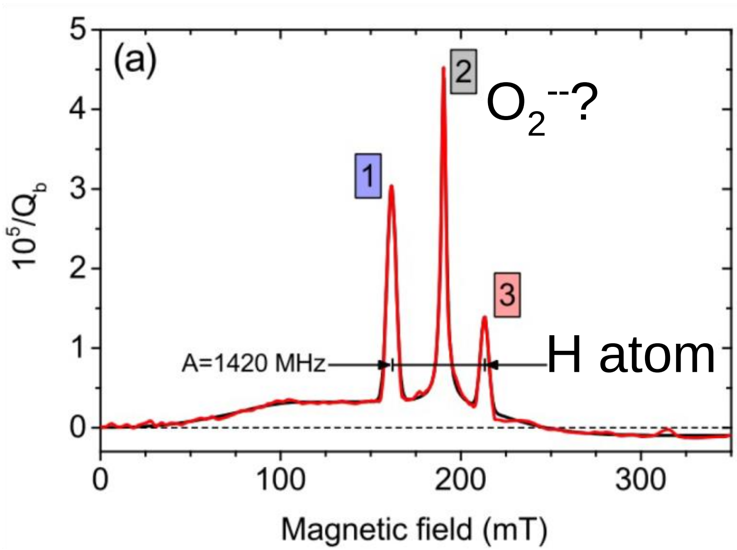




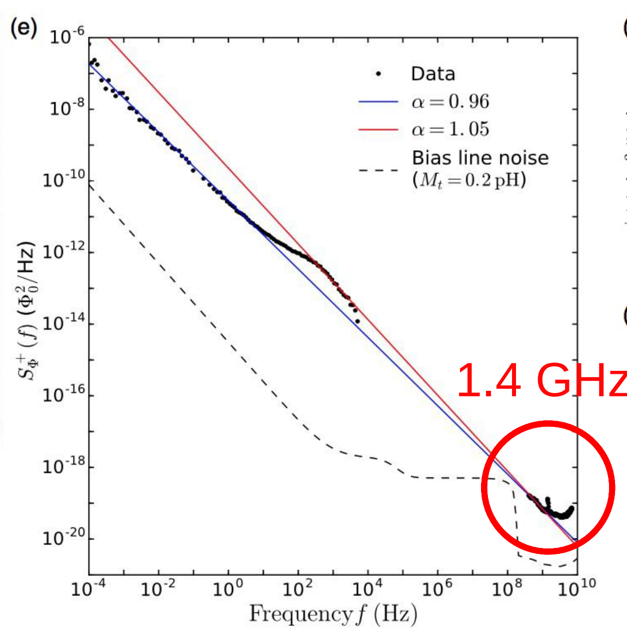
Molecular oxygen is paramagnetic. O_2 molecule has 2 unpaired electron spins in the triplet state (S=1) with magnetic moment = $2\mu_B$.

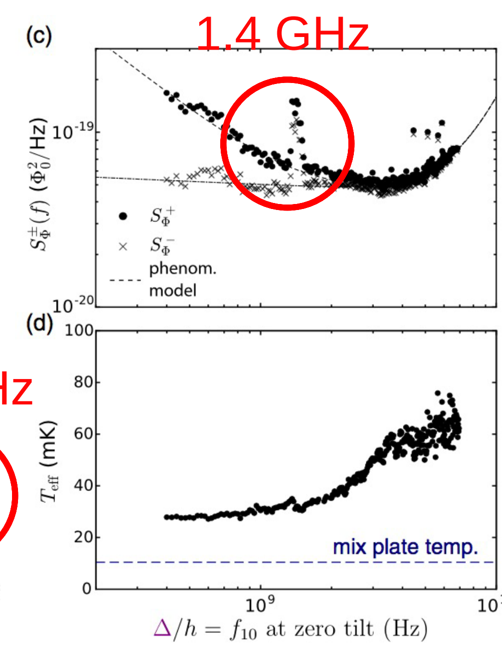
Another Flux Noise Source: Hydrogen Atoms

- **Surface treatments** do not remove all flux noise sources.
- **ESR measurements** on sapphire indicate hydrogen atoms
  - 1.42 GHz ESR line splitting matches free H atom
  - Flux noise measurements find ***peak at 1.4 GHz***
  - High frequency flux noise can cause qubit relaxation.



de Graaf *et al.* PRL 2017



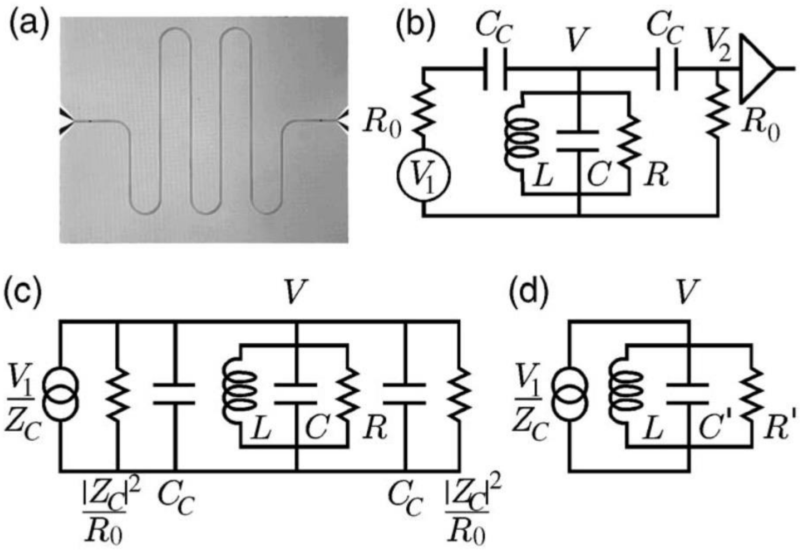


Quintana *et al.* PRL 2017

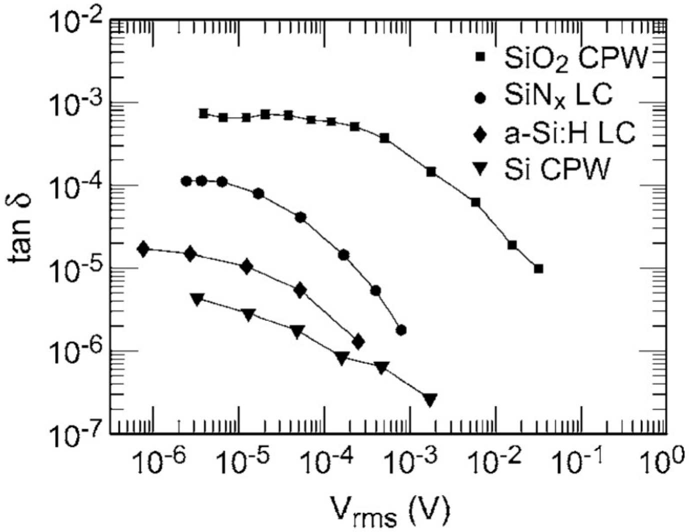
Summary of Flux Noise Superconducting SQUIDs

- Flux noise in SQUIDs is produced by magnetic impurities such as
  - Paramagnetic O_2 molecules adsorbed on the surface. This explains that
    - noise scales with surface area
    - flux noise independent of materials
  - Hydrogen atoms embedded in and adsorbed on metallic oxide layer and substrate
- Surface treatments can help remove impurities.

Candidate dielectrics for quantum circuits



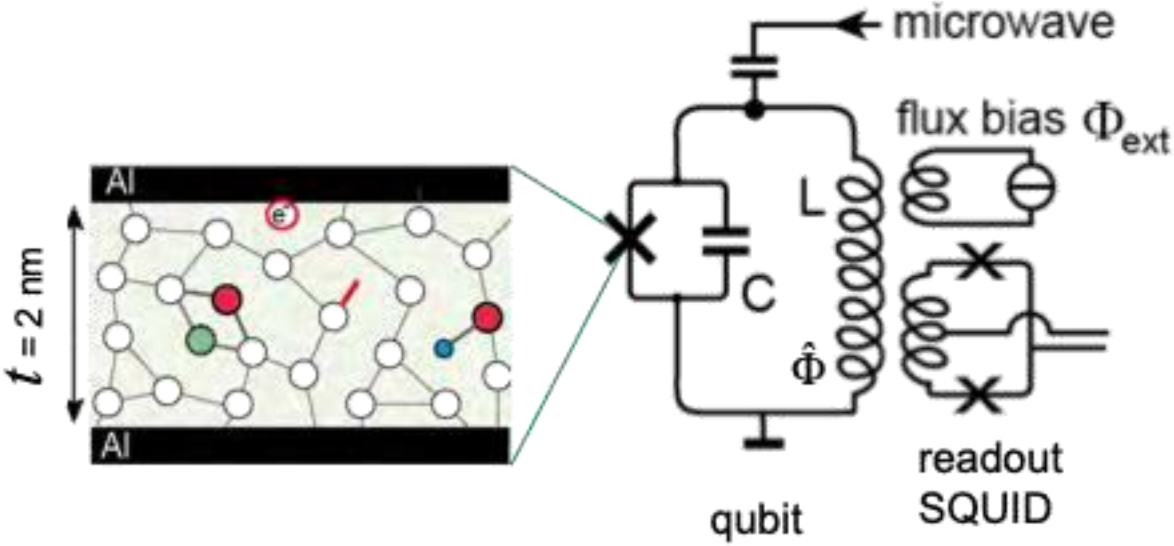
O'Connell et al., APL (08)

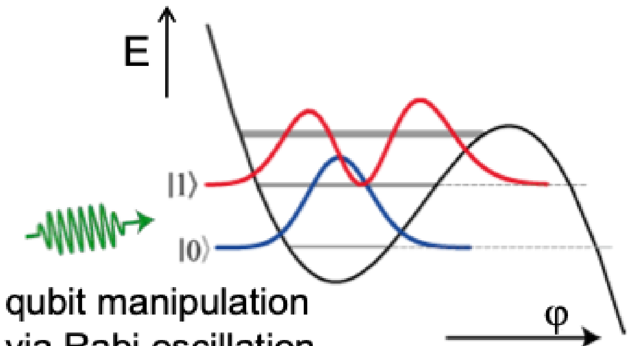


- a-Si:H has ~ factor 10 lower loss than SiNx
  (defects overconstrained from fourfold bond coordination?)
- Even in qubits with "simple" single-layer fabrication, lossy native oxides will limit T_1 times (2D transmon data compatible with surface loss)
- Crystalline dielectrics should be much better
- Surface chemistry of metals is also important (tantalum)

Tunneling Systems in Superconducting Quantum Devices

TLS – Qubit Interaction





Qubit-TLS interaction:
via TLS electrical dipole moment $\vec{p}$

Qubit:

$$\hat{H} = \frac{\hat{\Phi}^2}{2L} + \frac{\hat{Q}^2}{2C} + E_J$$

el. Field:

$$\vec{E} = \frac{\hat{Q}}{t\ C} \approx 1000\ \mathrm{V/m}$$

Dipole interaction:

for $\overline{p}$ = 2 D = 2 · 0.2 eÅ

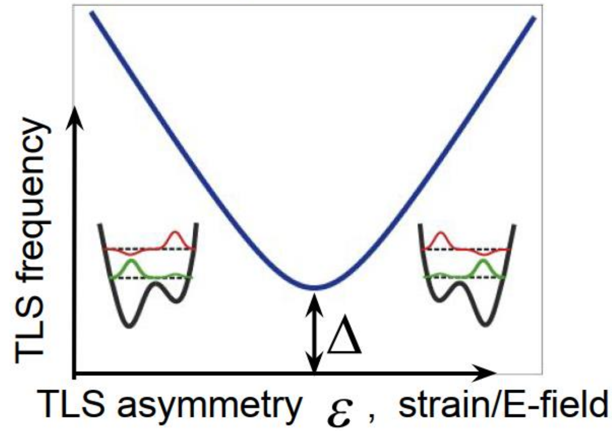
$$\Rightarrow\ g = \overline{p}\left|\vec{E}\right| \approx h \cdot 10\,\mathrm{MHz}$$

qubit-TLS coupling strength

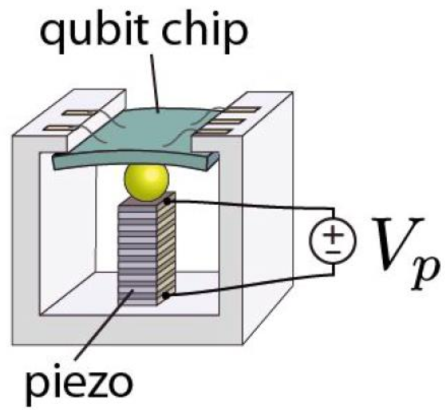
J.M. Martinis et al.,
PRL 93, 077003 (2004)

Two-Level-Systems Strain Spectroscopy

Tuning TLS by strain



strain control using a piezo



tiny deformations

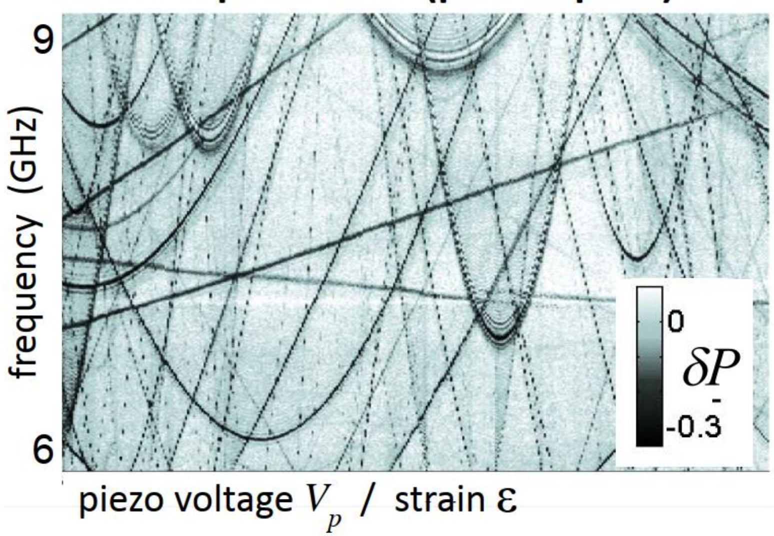
$$\frac{\Delta L}{L} \approx 10^{-7}\ /\mathrm{V}$$

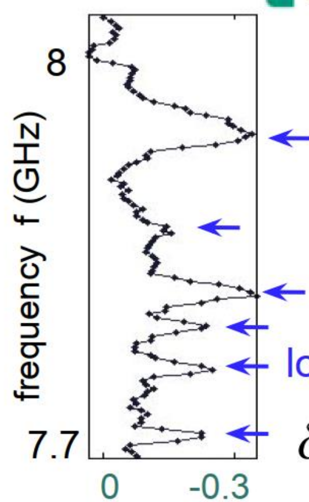
(compress 1 nm by 10^{-16} m)

change TLS asymmetry:

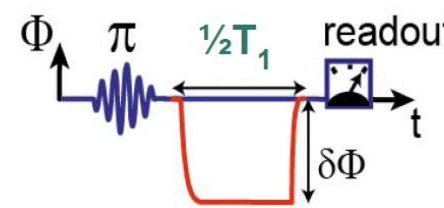
$$\varepsilon \approx 200\,\mathrm{MHz/V}$$

strain dependence (phase qubit)





Detect TLS by swap spectroscopy



loss due to resonant TLS

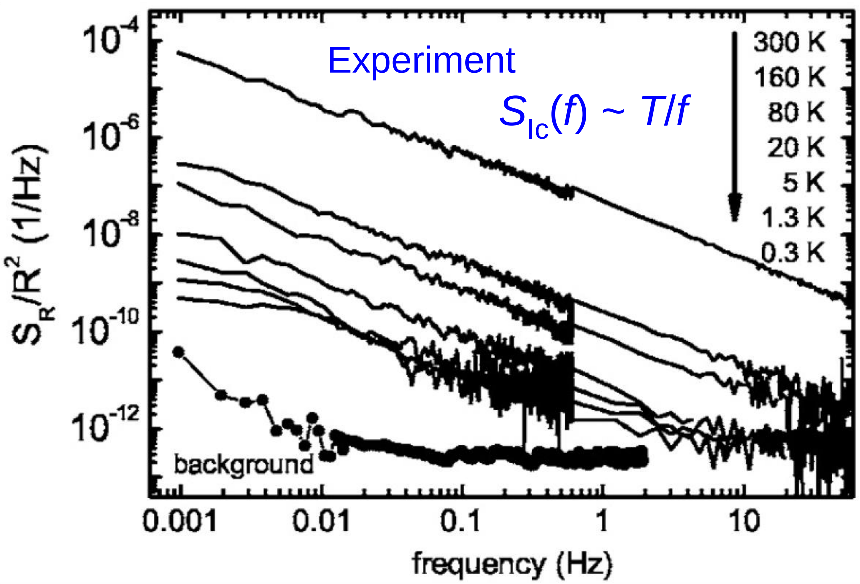
δP = loss in qubit population

G. Grabovskij, J. Lisenfeld, G. Weiss, A.V. Ustinov et al., *Science* **338**, 232 (2012)

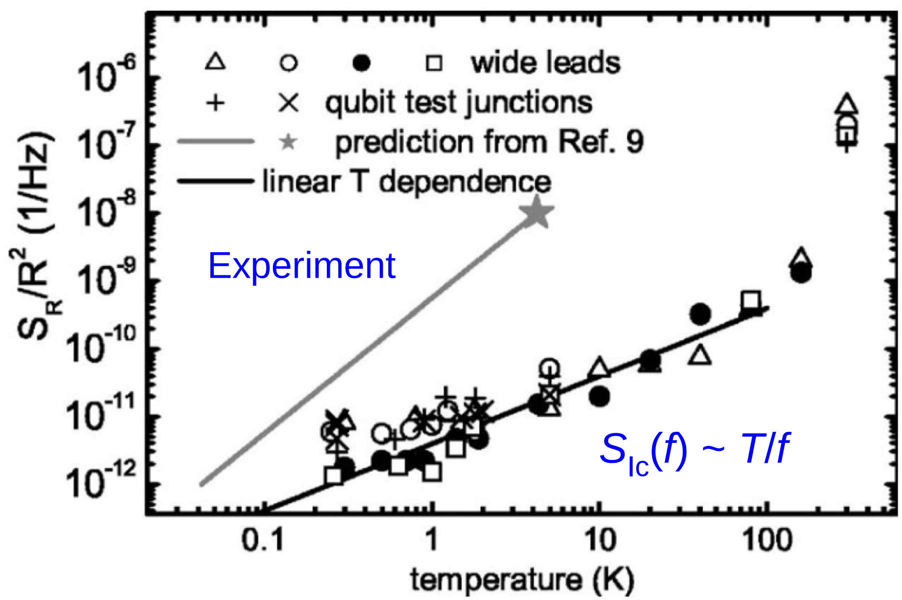
1/f Critical Current Noise

- Fluctuating TLS in the tunnel junction with electric dipole moment produce fluctuations in the tunneling matrix element resulting in 1/f noise in the critical current.

- TLS theory: $S_{\text{crit current}}(f) \sim TL^5/f$ (Constantin and Yu, 2007)
- Experiment on tunnel resistance: $S_R(f) \sim T/f$



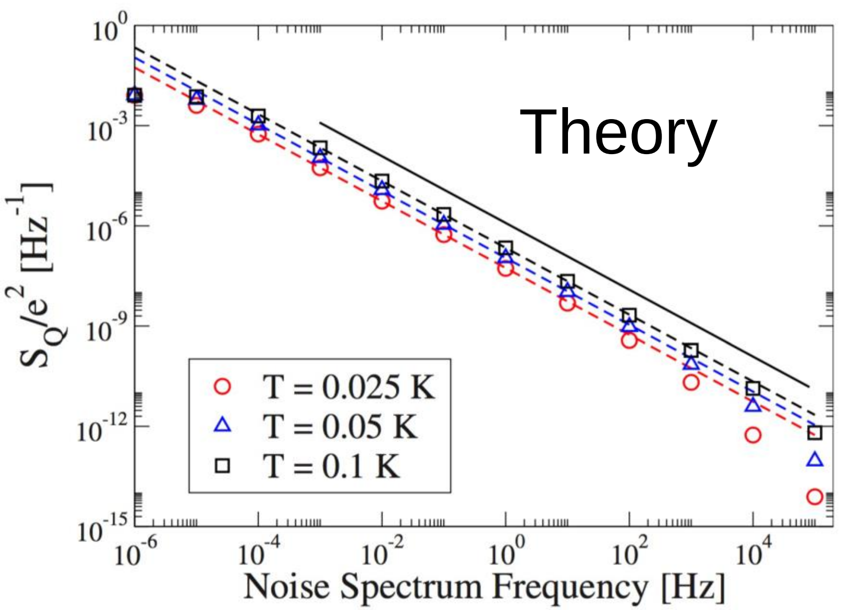
Eroms *et al*. 2006



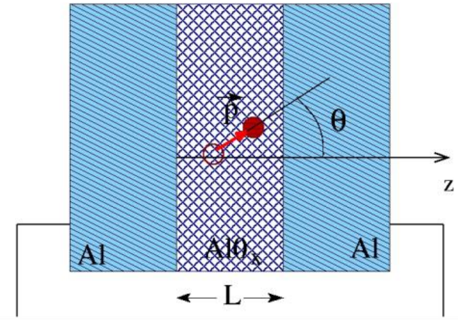
Eroms *et al*. 2006

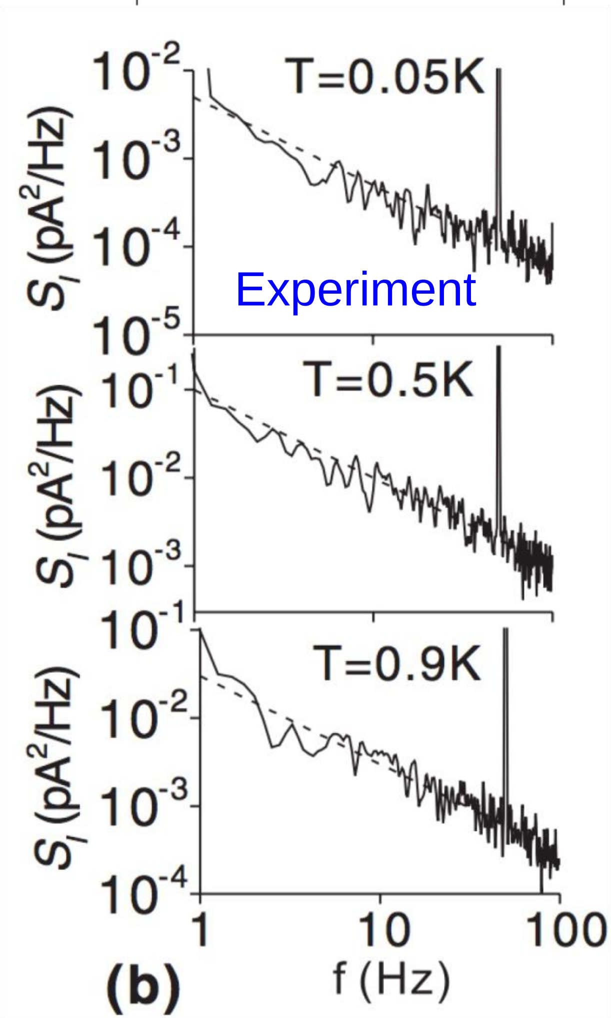
Charge Noise

- Fluctuating electric dipoles in tunnel junction barriers and insulating materials produce image charges in nearby superconductors and, hence, **low frequency** 1/f charge noise.
  - Experiment: $S_Q(f) \sim T^2/f$
  - TLS Theory: $S_Q(f) \sim T/f$



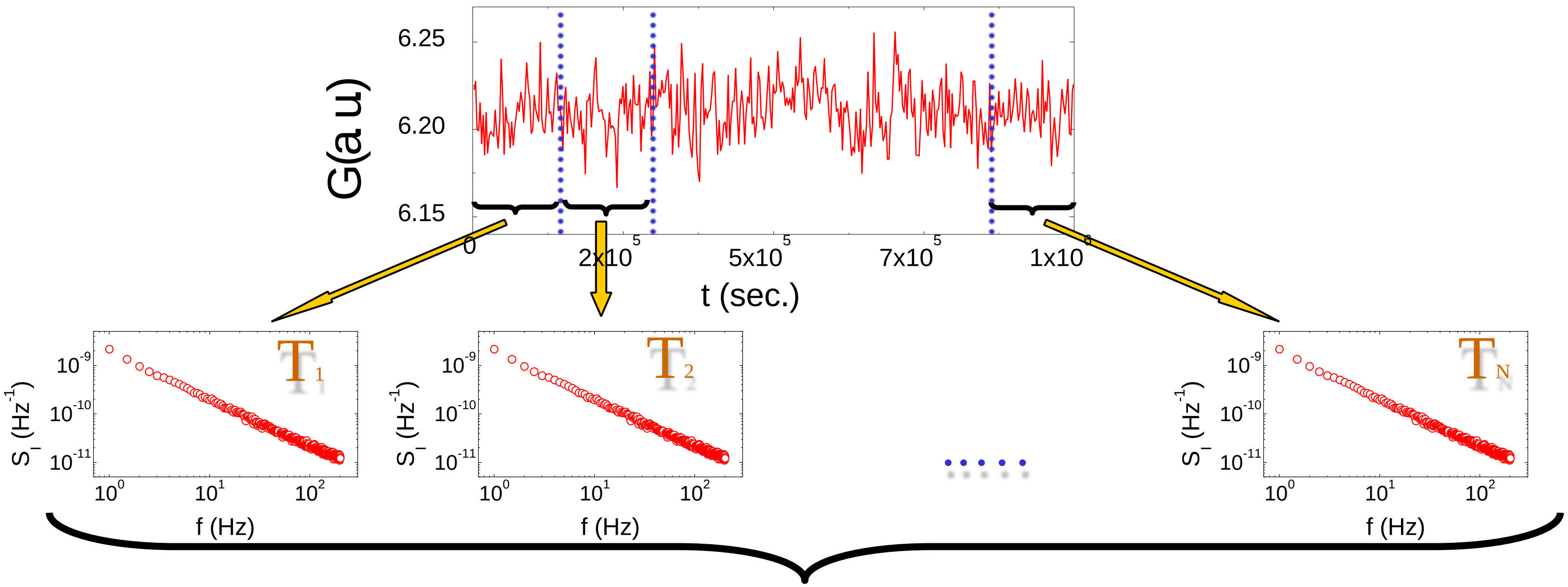
Constantin, Martinis, Yu 2009





Astafiev *et al.* 2006

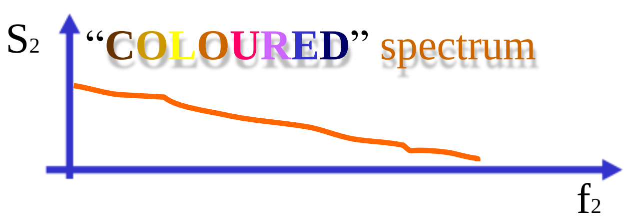
Second Spectrum – “NOISE of the NOISE”



$S_1(T_1,f)$, $S_1(T_2,f)$, …, $S_1(T_N,f)$

Octave summing $f_H=2f_L$, and FFT with respect to T

Uncorrelated fluctuators –
GAUSSIAN noise



Correlated fluctuators –
NON-GAUSSIAN noise

Summary of Squid Circuit Noise

- Flux noise in SQUIDs is produced by magnetic impurities such as
  - paramagnetic O_2 molecules adsorbed on the surface
  - H atoms embedded in and adsorbed on metallic oxide layer
- Fluctuating two level systems with electric dipole moments in the tunnel barrier and insulating materials produce
  - Dielectric loss
  - Energy splittings due to coupling with qubit energy levels
  - Charge noise
  - Critical current noise
- Need better and cleaner materials, fabrication processes, surface treatments, device designs, etc.