Physics 280 Quantum Mechanics Lecture III

Summer 2016

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Drexel University

August 17, 2016

Announcements

- Homework: practice final online by Friday morning

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- Can meet on campus in next two weeks: M,R 6-8; T: 6-9

Objectives

- Review QM Lecture II

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- Superconductors

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- EPR Paradox and Bell's Theorem

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- EPR Paradox and Bell's Theorem
- Consequences of Entanglement

- $$-\frac{\hbar^2}{2m}\frac{\partial^2\Psi(x,t)}{\partial x^2} + U\Psi(x,t) = i\hbar\frac{\partial\Psi(x,t)}{\partial t}$$

Schrödinger's Wave Equation

- $$-\frac{\hbar^2}{2m}\frac{\partial^2\Psi(x,t)}{\partial x^2}+U\Psi(x,t)=i\hbar\frac{\partial\Psi(x,t)}{\partial t}$$
- The time component can sometimes be broken away giving:

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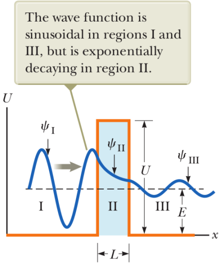
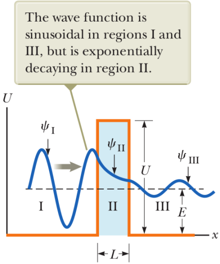
- The time component can sometimes be broken away giving:
- $$-\frac{\hbar^2}{2m}\frac{d^2\psi(x)}{dx^2} + U(x)\psi(x) = E\psi(x)$$

Tunneling


The wave function is sinusoidal in regions I and III, but is exponentially decaying in region II.
U
ψ_{I}
ψ_{II}
ψ_{III}
U
I
II
III
E
x
L

Tunneling

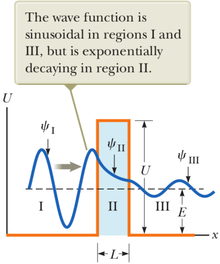


Recall that

$$C = \sqrt{\frac{2m(U-E)}{\hbar^2}}$$

It can be shown that the probability of an object tunneling through a barrier is:

Tunneling



Recall that

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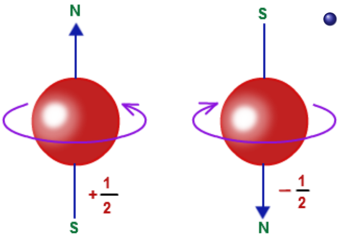
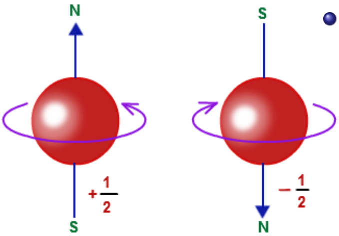
It can be shown that the probability of an object tunneling through a barrier is:

$$T \approx e^{-2CL}$$

Pauli Exclusion Principle



- An electron has intrinsic angular momentum, called **spin**. The image pictured at left is a classical model, **not** a quantum one. As far as we know, the electron is super super close to being a point particle.



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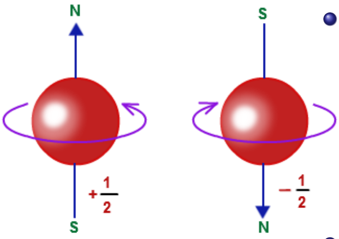

- An electron has intrinsic angular momentum, called **spin**. The image pictured at left is a classical model, **not** a quantum one. As far as we know, the electron is super super close to being a point particle.
- For an electron, the spin can be manifested as one of two types: spin up and spin down.
- The wave function for an electron needs to include its spin: $\psi(x) \rightarrow \psi(x) \uparrow or \psi(x) \downarrow$

Pauli Exclusion Principle

Because the Schrödinger equation is a differential equation, solutions can be combined to yield equally valid solutions. Consider two particles, 1 and 2, which can exist in states a or b: $\psi_a(x_1)$, $\psi_b(x_2)$, $\psi_a(x_2)$, and $\psi_b(x_1)$. The functions we can form turn out to correspond to two distinct types of particles:

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$$\psi_{1,2}(x) = A\left(\psi_a(x_1)\psi_b(x_2) + \psi_b(x_1)\psi_a(x_2)\right) \quad \text{Bosons}$$

$$\psi_{1,2}(x) = B\left(\psi_a(x_1)\psi_b(x_2) - \psi_b(x_1)\psi_a(x_2)\right) \quad \text{Fermions}$$

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For Fermions, the wave function goes to zero if the particles are in the exact same states ($\psi_a = \psi_b$).

Two identical fermion particles can not inhabit the exact same quantum state.

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Electrons are fermions. Why can't we fit a hundred electrons into the ground state of a hydrogen atom? How many can we fit?

Because electrons have intrinsic spin, either spin up or spin down, an electron in the ground state of a particular hydrogen atom can be distinguished from another electron in the ground state of that same atom if and only if they have opposite spins. Thus each energy level can contain two electrons and only two electrons so long as they have opposite spin.

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This **Pauli Exclusion Principle** is just one example of how *mathematics* is manifested in our *physical* universe. We will now look at another example of this manifestation.

Mystery:
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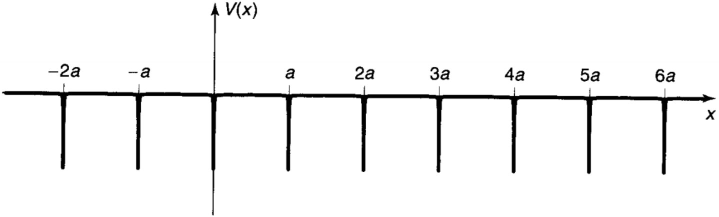
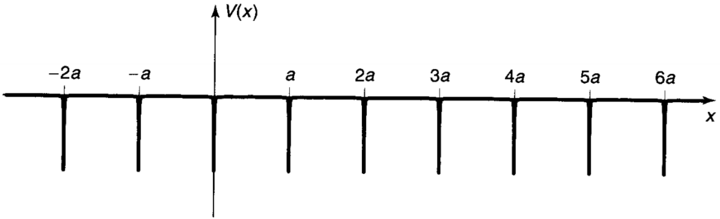
Why are some materials insulators and other materials conductors?

Dirac Comb:



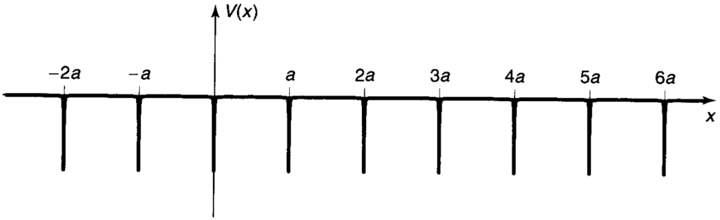
Models materials as a ”comb” of infinite potentials (the nucleus).

Band Structure

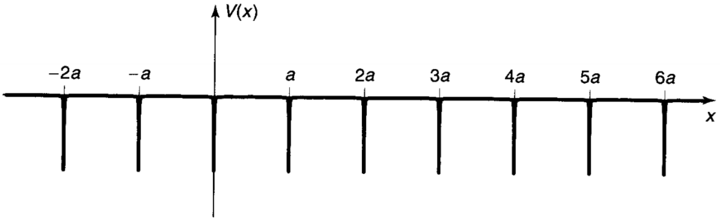


- The potential is periodic $V(x+a) = V(x)$.

Band Structure



- The potential is periodic $V(x+a) = V(x)$.
- Bloch's theorem gives $\psi(x+a) = e^{iKa}\psi(x)$ where K is a constant and i represents $\sqrt{-1}$



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- Let's focus on the solution for the block just to the left and right of the origin.

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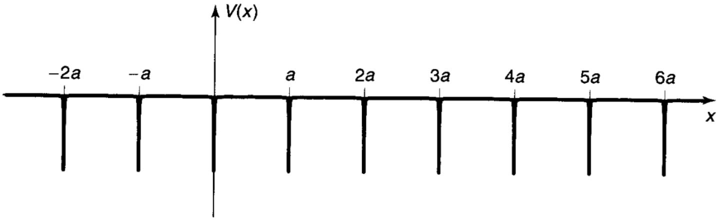

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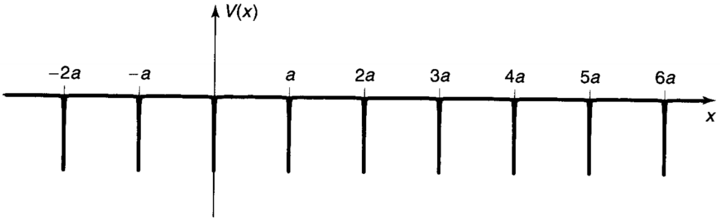
- Cell to right of origin:
  $\psi(x) = A\sin(kx) + B\cos(kx),\ 0 < x < a,\ k = \frac{\sqrt{2mE}}{\hbar}$

Band Structure



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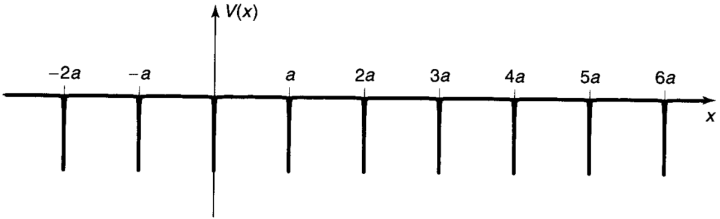

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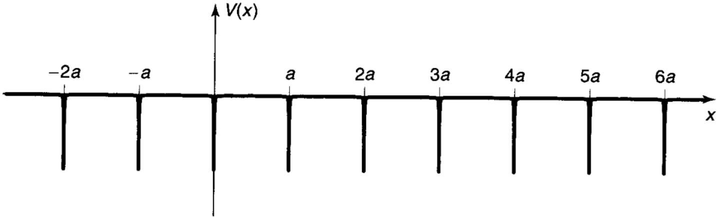

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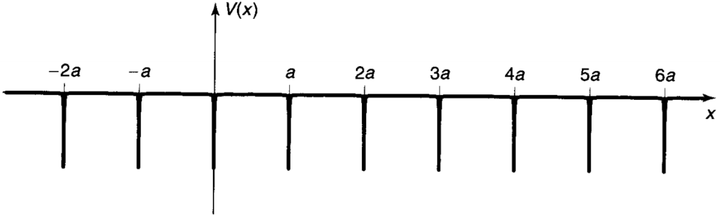
These equations must be continuous at their intersection $x = 0$. This yields the conditions:

$$B = e^{iKa}\left[A\sin(ka) + B\cos(ka)\right]$$

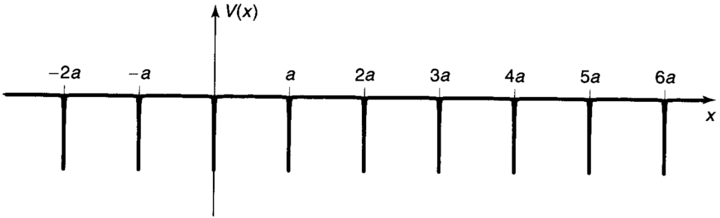
Band Structure



The derivatives must also be continues which yields:

$$kA - e^{-iKa}k\left[A\cos(ka) - B\sin(ka)\right] = -\frac{2m\alpha}{\hbar^2}B$$

where α is a constant depending on the material.



These two continuity conditions can be merged to yield:

$$\cos(Ka) = \cos(ka) - \frac{m\alpha}{\hbar^2 k}\sin(ka)$$

Note that thus far this is just a mathematical result, but it has interesting implications.

Band Structure

Let $z = ka$ and $\beta = \frac{m\alpha a}{\hbar^2}$ so that the continuity condition can be written:

$$f(z) = \cos(z) - \beta \frac{\sin(z)}{z}$$

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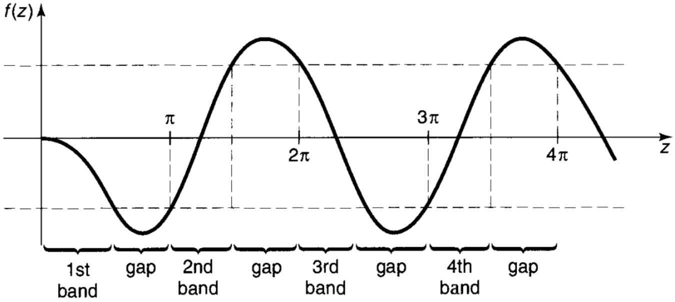

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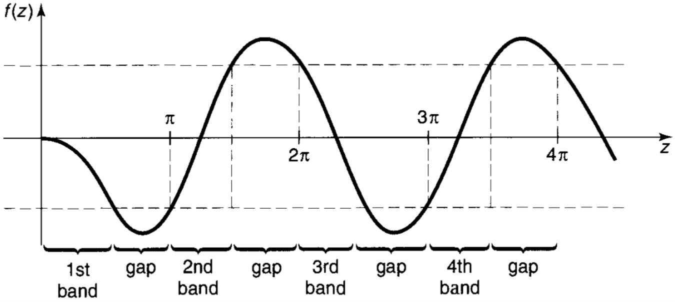
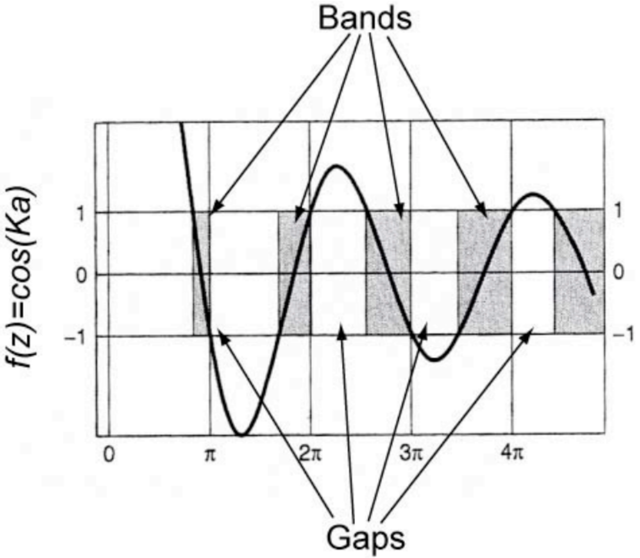


Can you spot the problem?

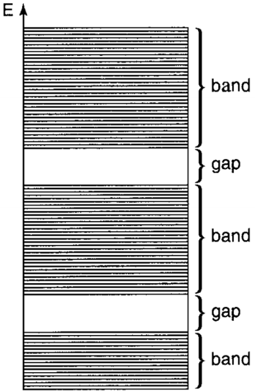
Band Structure

Since $|\cos(Ka)| \leq 1$, the equation only "works" in certain "bands":



Band Structure

This corresponds to areas in the Energy ”spectrum” which can never be occupied:



- Each energy band can have up to two electrons.

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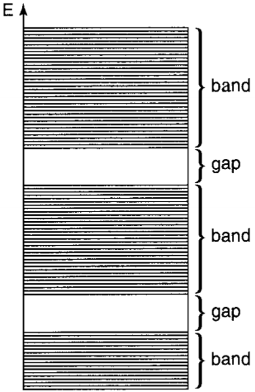

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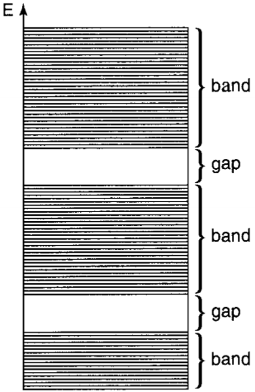

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- Electrons in these bands must make a quantum leap to higher energy bands but can never have energy equal to anywhere in the gap.
- If a gap is completely filled, takes a lot more energy to excite an electron to the next higher energy state since it has to "jump" across gap.

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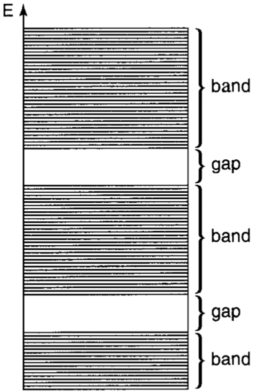

- In some materials, the lowest bands completely occupied with the material’s electrons already and it takes a lot of energy to jump the gap. These metals are insulators.

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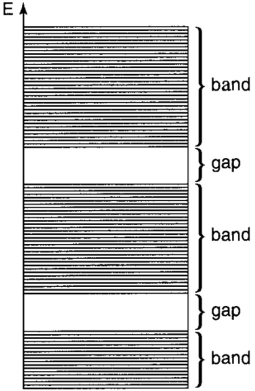

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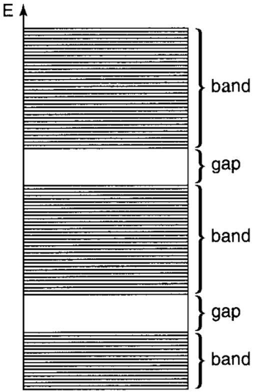

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- In other materials, the highest occupied band has room for more electrons and so it is easy to excite those electrons to higher energy states. These are conductors.
- ”Doping” of insulators can lead to semiconductors where either electrons are now in the next higher band or holes are in the previously filled one, and so weak currents can flow.

Band Structure

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Quantum Mechanics solves this mystery precisely. The solution shows us how deeply mathematics dictates the physical manifestation of the universe.

Mystery:
In classical physics we learn that all materials naturally have resistance to current.

- Items with relatively high resistance are insulators.

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Superconductors

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- Some materials see their resistivity drop to zero very quickly as their temperature is lowered.

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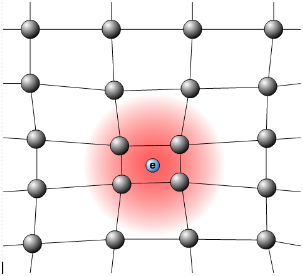
In classical physics we learn that all materials naturally have resistance to current.

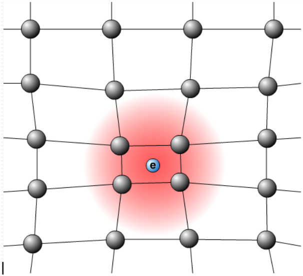
- Items with relatively high resistance are insulators.
- Items with relatively low resistance are conductors.
- Some materials see their resistivity drop to zero very quickly as their temperature is lowered.
- These ”SuperConductors” have no possible classical explanation.

Superconductors



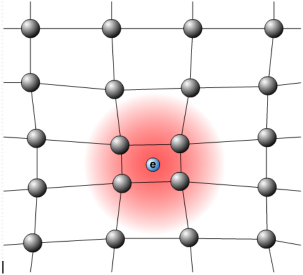
- An electron in a lattice of atoms/molecules will attract positive charge towards it, warping the lattice and creating an area of enhanced positivity that attracts another electron

Superconductors



- An electron in a lattice of atoms/molecules will attract positive charge towards it, warping the lattice and creating an area of enhanced positivity that attracts another electron
- another electron comes along and interacts with this area, becoming bound and creating "Cooper pairs" if and only if it has opposite spin (Pauli Exclusion)

Superconductors



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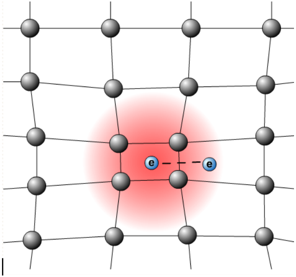
- another electron comes along and interacts with this area, becoming bound and creating "Cooper pairs" if and only if it has opposite spin (Pauli Exclusion)
- They need not be stationary as long as they continue to "warp" the lattice as they move along.

Superconductors



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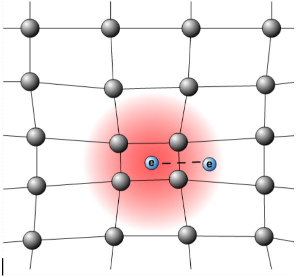

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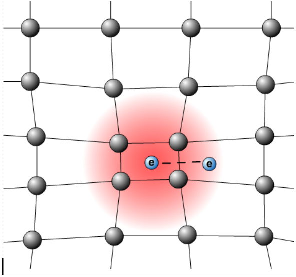

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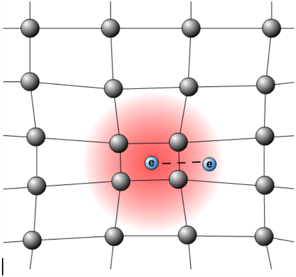
Superconductors



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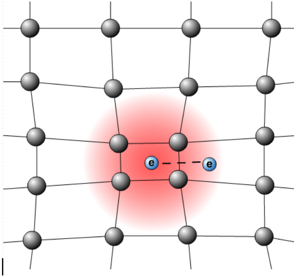
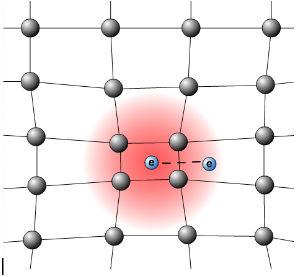
- The energy of the ground state of a cooper pair is lower than the energy of the ground state of the electrons unpaired (Band Gap) and **correlated** with the total energy of all cooper pairs.
- This makes it hard to break the bond; kicks from thermal energy can do so.

Superconductors



- Cooper pairs have a wave function that is boson-like
- This means that you can have unlimited pairs in the lowest energy state where they begin to cluster as your lower temperature
- The energy of the ground state of a cooper pair is lower than the energy of the ground state of the electrons unpaired (Band Gap) and **correlated** with the total energy of all cooper pairs.
- This makes it hard to break the bond; kicks from thermal energy can do so.
- When thermal energy goes below this band gap, resistivity vanishes.

Superconductors



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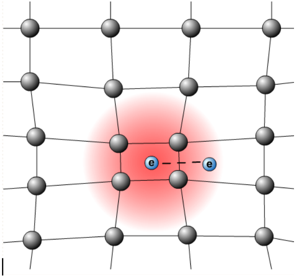

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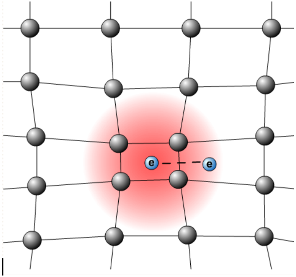

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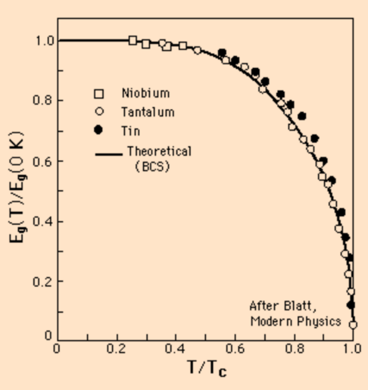
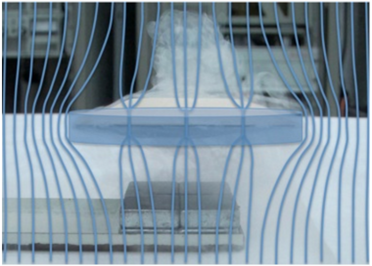
- All cooper pairs behave as a quantum collective and are ”immune” from any further effects of thermal kicks.
- A rough analogy would be a boss trying to fire a Union worker without cause. Such a boss would have to overcome the collective power of the Union to do so, rather than one pretty helpless employee.



Measurements of the actual band-gap (microwave absorption experiments) vs. BCS prediction. As we increase temperature from well below T_c to the critical temperature T_c, the gap vanishes.



Meissner effect:

Link

Quantum Locking:

Link

Entanglement

A neutral pi meson decays into an electron and positron:

$$\pi^0 \to e^- + e^+$$

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Conservation of momentum requires that the electron and positron our in the state:

$$\frac{1}{\sqrt{2}}\left(\uparrow_-\downarrow_+ - \downarrow_-\uparrow_+\right)$$

(why this state is beyond the scope of this class but mathematically dictated by Schrodinger's Equation..it's the state corresponding to effective spin zero)

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- You automatically know that the positron is $\downarrow$ and anyone measuring it would find that result.

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- Einstein lost. The electron and positron are **entangled**.

Entanglement

Nature is fundamentally *nonlocal*. Whatever is going on with the electron and the positron is something spread throughout the wavefunction.

Information is **not** being transmitted faster than light because, in part, quantum effects are seen in statistical ensembles.

Quantum Cryptography: One thing Entanglement leads to is unbreakable cryptography. Link

Link

Final Note

It gets worse....

Link