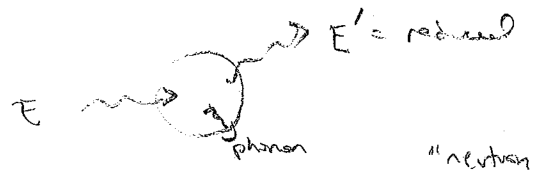
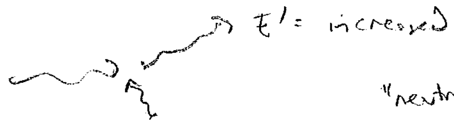
## Inelastic scattering of neutrons




"neutron emits a phonon"

$$E_f = E_i - \hbar\omega$$

$$\vec{p}_f = \vec{p}_i - \hbar\vec{k}$$




"neutron absorbs a phonon"

$$E_f = E_i + \hbar\omega$$

$$\vec{p}_f = \vec{p}_i + \hbar\vec{k}$$

Use cons. of energy + cons. of momentum to analyze problem

Next page
Worked problem: Which exact phonon produced peak A?

(HW: " " " " " B)

TOPS. 35500

day 16 pg 2

From Stokes, *Solid State Physics for Advanced Undergraduate Students*

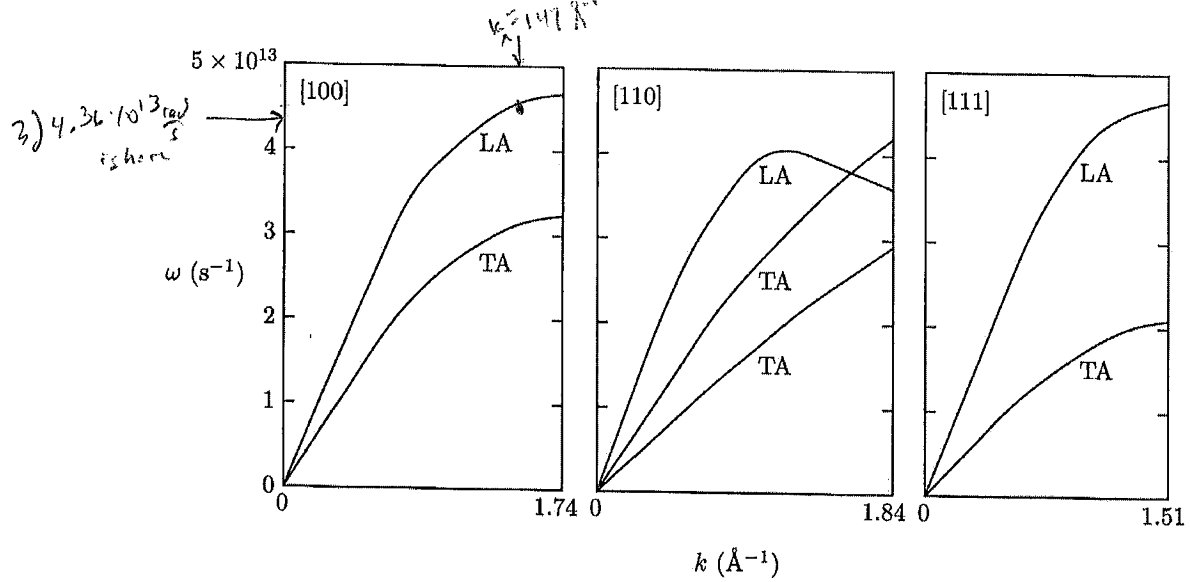



Fig. 3-21. Dispersion curves in copper (Cu) along the dashed lines shown for the first Brillouin zone in Fig. 3-19. Data are from E. C. Svensson, B. N. Brockhouse, and J. M. Rowe, *Phys. Rev.* **155**, 619 (1967).

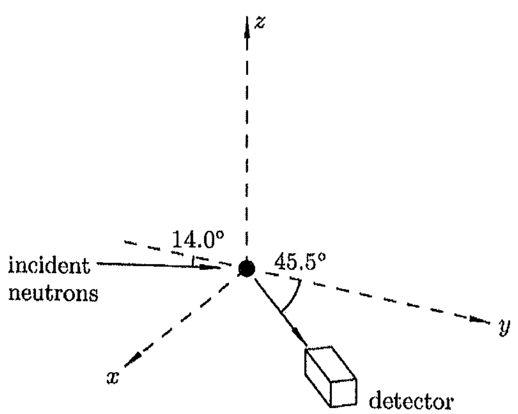



Fig. 5-3. Directions of incident and scattered neutrons for the spectrum in Fig. 5-2.

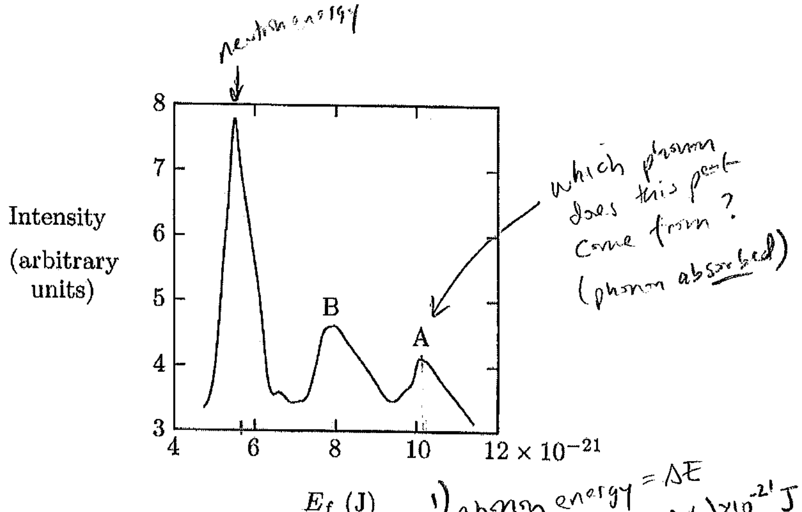



Fig. 5-2. Inelastic scattering of neutrons from copper. Reprinted with permission from *J. Phys. Chem. Solids* **23**, J. Sosnowski and J. Kuzubowski, "Phonon dispersion relations for copper single crystal in the [100] direction," Copyright 1962, Pergamon Press, Ltd.

1) phonon energy = $\Delta E = (10.2 - 5.6) \times 10^{-21}$ J $= 4.6 \times 10^{-21}$ J

2) phonon ω

$\omega = E/\hbar = \frac{4.6 \cdot 10^{-21}\text{ J}}{6.626 \cdot 10^{-34}/2\pi} = 4.36 \cdot 10^{13}$ rad/s

4) What was momentum?

Neutron: $E = \frac{1}{2}mv^2 = \frac{p^2}{2m}$ (non relativistic)

$p = \sqrt{2mE}$ ← mass of neutron

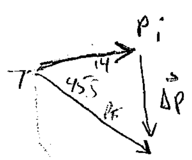
$p_i = \sqrt{2(1.675 \cdot 10^{-27})(5.6 \cdot 10^{-21})} = 4.331 \cdot 10^{-24}$ kg m/s

$p_f = \sqrt{2(1.675 \cdot 10^{-27})(10.2 \cdot 10^{-21})} = 5.846 \cdot 10^{-24}$ kg m/s

$\hbar \vec{k}_{phonon} = \Delta\vec{p} = 5.846 \angle 44.5° - 4.331 \angle 104.0° = 5.277 \cdot 10^{-24}\,\hat{x} - .1055 \cdot 10^{-24}\,\hat{y}$

$k_x = 4.999 \cdot 10^{10}$ m⁻¹ → phonon outside 1st BZ; subtract off $\vec{G} = \frac{4\pi}{a}\hat{x} = \frac{4\pi}{3.61 \cdot 10^{-10}}\hat{x}$

$k_y = -.100 \cdot 10^{10}$ m⁻¹ then $k_x = 1.466 \cdot 10^{10}$ m⁻¹



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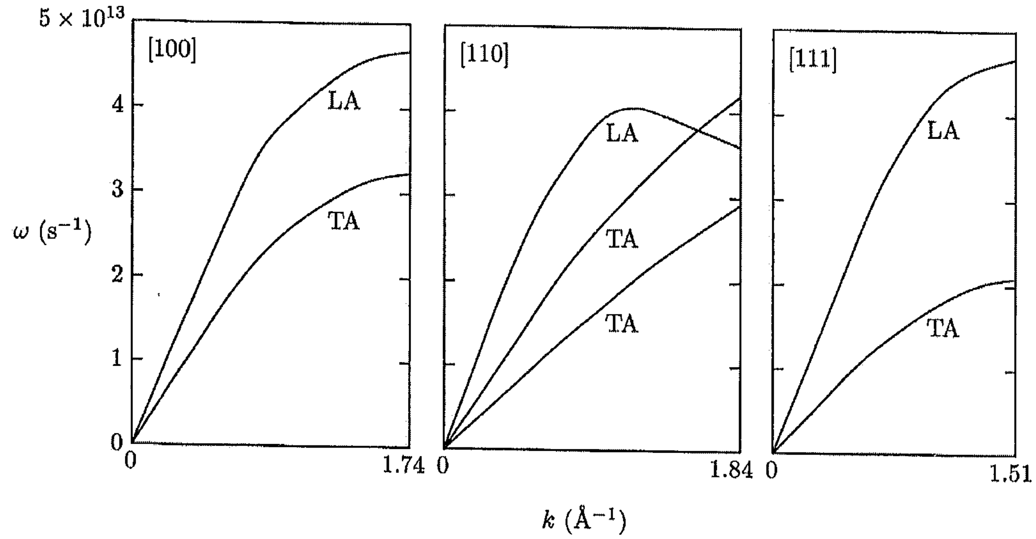


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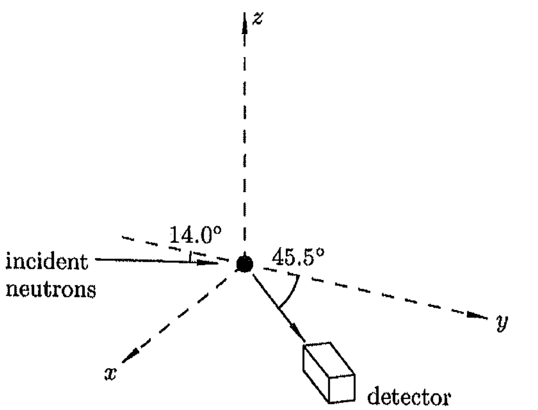


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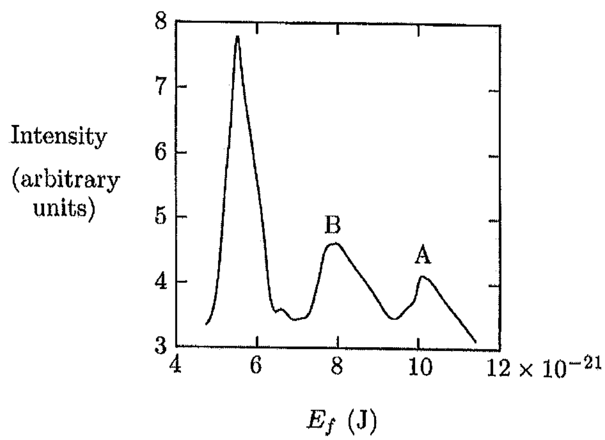


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day 16 pg 3

Chapter 5! "Phonons II, Thermal Properties"

Last lecture:

$(n+\frac{1}{2})\hbar\omega$ = energy for all phonons $(n)$ with frequency $\omega$.

How many phonons is that?

Answer: $n_{ave} = \frac{1}{e^{\hbar\omega/kT} - 1}$

$k = k_B = 1.38\ 10^{-23}\ J/K$ Not wavevector!

Kittel: sometimes $\tau = kT$

Where does that come from?

Two major results of Physics 360: What's likelihood of a given energy state E being occupied?

**Bose Einstein Distribution**

$n_{ave} = \frac{1}{e^{(E-\mu)/kT} - 1}$

for particles w/o Pauli exclusion (photons, phonons, etc) "Bosons"

Side note: $n_{ave} \to \infty$ as $T \to 0$ "Bose Einstein Condensation" ↓ or at least very big ($\mu$ changes w/ temp too)

**Fermi-Dirac Distribution**

$n_{ave} = \frac{1}{e^{(E-\mu)/kT} + 1}$

for particles w/ Pauli exclusion (electrons, protons, neutrons, etc) "Fermions"

$\mu$ = "Chemical Potential", needed if you have a fixed # of particles $\Delta E = \mu \Delta N$ I think

For photons/phonons: $\mu = 0$ because you can add/take away particles with no problem.

day 17 pg 1

Boltzmann distribution

$n_{ave} = N_{tot} \frac{e^{-E/kT}}{\sum_{all\ BFs}}$ ← or really $(E-\mu)/kT$

if $E \gg \mu$, all three are the same