

Molecules and Solids

CHAPTER OUTLINE

- 43.1 Molecular Bonds
- 43.2 Energy States and Spectra of Molecules
- 43.3 Bonding in Solids
- 43.4 Free-Electron Theory of Metals
- 43.5 Band Theory of Solids
- 43.6 Electrical Conduction in Metals, Insulators, and Semiconductors
- 43.7 Semiconductor Devices
- 43.8 Superconductivity

ANSWERS TO QUESTIONS

Q43.1 Ionic bonds are ones between oppositely charged ions. A simple model of an ionic bond is the electrostatic attraction of a negatively charged latex balloon to a positively charged Mylar balloon.

Covalent bonds are ones in which atoms share electrons. Classically, two children playing a short-range game of catch with a ball models a covalent bond. On a quantum scale, the two atoms are sharing a wave function, so perhaps a better model would be two children using a single hula hoop.

Van der Waals bonds are weak electrostatic forces: the dipole-dipole force is analogous to the attraction between the opposite poles of two bar magnets, the dipole-induced dipole force is similar to a bar magnet attracting an iron nail or paper clip, and the dispersion force is analogous to an alternating-current electro-magnet attracting a paper clip.

A hydrogen atom in a molecule is not ionized, but its electron can spend more time elsewhere than it does in the hydrogen atom. The hydrogen atom can be a location of net positive charge, and can weakly attract a zone of negative charge in another molecule.

Q43.2 Rotational, vibrational, and electronic (as discussed in Chapter 42) are the three major forms of excitation. Rotational energy for a diatomic molecule is on the order of $\frac{\hbar^2}{2I}$, where I is the moment of inertia of the molecule. A typical value for a small molecule is on the order of $1 \text{ meV} = 10^{-3} \text{ eV}$. Vibrational energy is on the order of $\hbar f$, where f is the vibration frequency of the molecule. A typical value is on the order of 0.1 eV . Electronic energy depends on the state of an electron in the molecule and is on the order of a few eV. The rotational energy can be zero, but neither the vibrational nor the electronic energy can be zero.

***Q43.3** If you start with a solid sample and raise its temperature, it will typically melt first, then start emitting lots of far infrared light, then emit light with a spectrum peaking in the near infrared, and later have its molecules dissociate into atoms. Rotation of a diatomic molecule involves less energy than vibration. Absorption and emission of microwave photons, of frequency $\sim 10^{11} \text{ Hz}$, accompany excitation and de-excitation of rotational motion, while infrared photons, of frequency $\sim 10^{13} \text{ Hz}$, accompany changes in the vibration state of typical simple molecules. The ranking is then $b > d > c > a$.

- Q43.4** From the rotational spectrum of a molecule, one can easily calculate the moment of inertia of the molecule using Equation 43.7 in the text. Note that with this method, only the spacing between adjacent energy levels needs to be measured. From the moment of inertia, the size of the molecule can be calculated, provided that the structure of the molecule is known.
- *Q43.5** Answer (b). At higher temperature, molecules are typically in higher rotational energy levels before as well as after infrared absorption.
- *Q43.6** (i) Answer (a). An example is NaCl, table salt.
 (ii) Answer (b). Examples are elemental silicon and carborundum (silicon carbide).
 (iii) Answer (c). Think of aluminum foil.
- *Q43.7** (i) Answer (b). The density of states is proportional to the energy to the one-half power.
 (ii) Answer (a). Most states well above the Fermi energy are unoccupied.
- Q43.8** In a metal, there is no energy gap between the valence and conduction bands, or the conduction band is partly full even at absolute zero in temperature. Thus an applied electric field is able to inject a tiny bit of energy into an electron to promote it to a state in which it is moving through the metal as part of an electric current. In an insulator, there is a large energy gap between a full valence band and an empty conduction band. An applied electric field is unable to give electrons in the valence band enough energy to jump across the gap into the higher energy conduction band. In a semiconductor, the energy gap between valence and conduction bands is smaller than in an insulator. At absolute zero the valence band is full and the conduction band is empty, but at room temperature thermal energy has promoted some electrons across the gap. Then there are some mobile holes in the valence band as well as some mobile electrons in the conduction band.
- *Q43.9** Answer (b). First consider electric conduction in a metal. The number of conduction electrons is essentially fixed. They conduct electricity by having drift motion in an applied electric field superposed on their random thermal motion. At higher temperature, the ion cores vibrate more and scatter more efficiently the conduction electrons flying among them. The mean time between collisions is reduced. The electrons have time to develop only a lower drift speed. The electric current is reduced, so we see the resistivity increasing with temperature.
 Now consider an intrinsic semiconductor. At absolute zero its valence band is full and its conduction band is empty. It is an insulator, with very high resistivity. As the temperature increases, more electrons are promoted to the conduction band, leaving holes in the valence band. Then both electrons and holes move in response to an applied electric field. Thus we see the resistivity decreasing as temperature goes up.
- Q43.10** The energy of the photon is given to the electron. The energy of a photon of visible light is sufficient to promote the electron from the lower-energy valence band to the higher-energy conduction band. This results in the additional electron in the conduction band and an additional hole—the energy state that the electron used to occupy—in the valence band.
- Q43.11** Along with arsenic (As), any other element in group V, such as phosphorus (P), antimony (Sb), and bismuth (Bi), would make good donor atoms. Each has 5 valence electrons. Any element in group III would make good acceptor atoms, such as boron (B), aluminum (Al), gallium (Ga), and indium (In). They all have only 3 valence electrons.
- Q43.12** The two assumptions in the free-electron theory are that the conduction electrons are not bound to any particular atom, and that the nuclei of the atoms are fixed in a lattice structure. In this model, it is the “soup” of free electrons that are conducted through metals. The energy band model is more comprehensive than the free-electron theory. The energy band model includes an account of the more tightly bound electrons as well as the conduction electrons. It can be developed into a theory of the structure of the crystal and its mechanical and thermal properties.

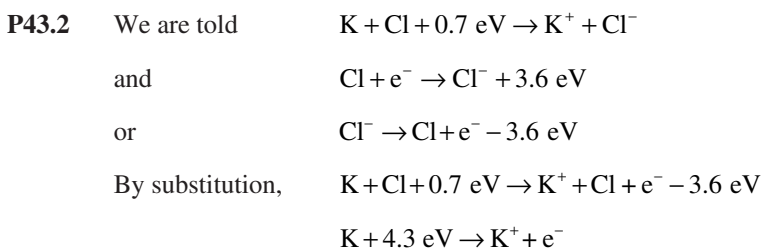
- Q43.13** A molecule containing two atoms of ^2H , deuterium, has twice the mass of a molecule containing two atoms of ordinary hydrogen ^1H . The atoms have the same electronic structure, so the molecules have the same interatomic spacing, and the same spring constant. Then the moment of inertia of the double-deuteron is twice as large and the rotational energies one-half as large as for ordinary hydrogen. Each vibrational energy level for D_2 is $\frac{1}{\sqrt{2}}$ times that of H_2 .
- Q43.14** Yes. A material can absorb a photon of energy greater than the energy gap, as an electron jumps into a higher energy state. If the photon does not have enough energy to raise the energy of the electron by the energy gap, then the photon will not be absorbed.
- *Q43.15** (i) and (ii) Answer (a) for both. Either kind of doping contributes more mobile charge carriers, either holes or electrons.
- *Q43.16** (a) false (b) false (c) true (d) true (e) true

SOLUTIONS TO PROBLEMS

Section 43.1 Molecular Bonds

P43.1 (a) $F = \frac{q^2}{4\pi\epsilon_0 r^2} = \frac{(1.60 \times 10^{-19})^2 (8.99 \times 10^9)}{(5.00 \times 10^{-10})^2} \text{ N} = \boxed{0.921 \times 10^{-9} \text{ N}}$ toward the other ion.

(b) $U = \frac{-q^2}{4\pi\epsilon_0 r} = -\frac{(1.60 \times 10^{-19})^2 (8.99 \times 10^9)}{5.00 \times 10^{-10}} \text{ J} \approx \boxed{-2.88 \text{ eV}}$



or the ionization energy of potassium is $\boxed{4.3 \text{ eV}}$.

- P43.3** (a) Minimum energy of the molecule is found from

$$\frac{dU}{dr} = -12Ar^{-13} + 6Br^{-7} = 0 \text{ yielding } r_0 = \left[\frac{2A}{B} \right]^{1/6}$$

(b) $E = U|_{r=\infty} - U|_{r=r_0} = 0 - \left[\frac{A}{4A^2/B^2} - \frac{B}{2A/B} \right] = -\left[\frac{1}{4} - \frac{1}{2} \right] \frac{B^2}{A} = \boxed{\frac{B^2}{4A}}$

This is also the equal to the binding energy, the amount of energy given up by the two atoms as they come together to form a molecule.

(c) $r_0 = \left[\frac{2(0.124 \times 10^{-120} \text{ eV} \cdot \text{m}^{12})}{1.488 \times 10^{-60} \text{ eV} \cdot \text{m}^6} \right]^{1/6} = 7.42 \times 10^{-11} \text{ m} = \boxed{74.2 \text{ pm}}$

$$E = \frac{(1.488 \times 10^{-60} \text{ eV} \cdot \text{m}^6)^2}{4(0.124 \times 10^{-120} \text{ eV} \cdot \text{m}^{12})} = \boxed{4.46 \text{ eV}}$$

- P43.4** (a) We add the reactions $K + 4.34 \text{ eV} \rightarrow K^+ + e^-$
 and $I + e^- \rightarrow I^- + 3.06 \text{ eV}$
 to obtain $K + I \rightarrow K^+ + I^- + (4.34 - 3.06) \text{ eV}$
 The activation energy is $\boxed{1.28 \text{ eV}}$.

$$(b) \quad \frac{dU}{dr} = \frac{4\epsilon}{\sigma} \left[-12 \left(\frac{\sigma}{r} \right)^{13} + 6 \left(\frac{\sigma}{r} \right)^7 \right]$$

At $r = r_0$ we have $\frac{dU}{dr} = 0$. Here $\left(\frac{\sigma}{r_0} \right)^{13} = \frac{1}{2} \left(\frac{\sigma}{r_0} \right)^7$

$$\frac{\sigma}{r_0} = 2^{-1/6} \quad \sigma = 2^{-1/6} (0.305) \text{ nm} = \boxed{0.272 \text{ nm} = \sigma}$$

Then also

$$U(r_0) = 4\epsilon \left[\left(\frac{2^{-1/6} r_0}{r_0} \right)^{12} - \left(\frac{2^{-1/6} r_0}{r_0} \right)^6 \right] + E_a = 4\epsilon \left[\frac{1}{4} - \frac{1}{2} \right] + E_a = -\epsilon + E_a$$

$$\epsilon = E_a - U(r_0) = 1.28 \text{ eV} + 3.37 \text{ eV} = \boxed{4.65 \text{ eV} = \epsilon}$$

$$(c) \quad F(r) = -\frac{dU}{dr} = \frac{4\epsilon}{\sigma} \left[12 \left(\frac{\sigma}{r} \right)^{13} - 6 \left(\frac{\sigma}{r} \right)^7 \right]$$

To find the maximum force we calculate $\frac{dF}{dr} = \frac{4\epsilon}{\sigma^2} \left[-156 \left(\frac{\sigma}{r} \right)^{14} + 42 \left(\frac{\sigma}{r} \right)^8 \right] = 0$ when

$$\frac{\sigma}{r_{\text{rupture}}} = \left(\frac{42}{156} \right)^{1/6}$$

$$F_{\text{max}} = \frac{4(4.65 \text{ eV})}{0.272 \text{ nm}} \left[12 \left(\frac{42}{156} \right)^{13/6} - 6 \left(\frac{42}{156} \right)^{7/6} \right] = -41.0 \text{ eV/nm} = -41.0 \frac{1.6 \times 10^{-19} \text{ Nm}}{10^{-9} \text{ m}}$$

$$= -6.55 \text{ nN}$$

Therefore the applied force required to rupture the molecule is $\boxed{+6.55 \text{ nN}}$ away from the center.

$$(d) \quad U(r_0 + s) = 4\epsilon \left[\left(\frac{\sigma}{r_0 + s} \right)^{12} - \left(\frac{\sigma}{r_0 + s} \right)^6 \right] + E_a = 4\epsilon \left[\left(\frac{2^{-1/6} r_0}{r_0 + s} \right)^{12} - \left(\frac{2^{-1/6} r_0}{r_0 + s} \right)^6 \right] + E_a$$

$$= 4\epsilon \left[\frac{1}{4} \left(1 + \frac{s}{r_0} \right)^{-12} - \frac{1}{2} \left(1 + \frac{s}{r_0} \right)^{-6} \right] + E_a$$

$$= 4\epsilon \left[\frac{1}{4} \left(1 - 12 \frac{s}{r_0} + 78 \frac{s^2}{r_0^2} - \dots \right) - \frac{1}{2} \left(1 - 6 \frac{s}{r_0} + 21 \frac{s^2}{r_0^2} - \dots \right) \right] + E_a$$

$$= \epsilon - 12\epsilon \frac{s}{r_0} + 78\epsilon \frac{s^2}{r_0^2} - 2\epsilon + 12\epsilon \frac{s}{r_0} - 42\epsilon \frac{s^2}{r_0^2} + E_a + \dots$$

$$= -\epsilon + E_a + 0 \left(\frac{s}{r_0} \right) + 36\epsilon \frac{s^2}{r_0^2} + \dots$$

$$U(r_0 + s) \approx U(r_0) + \frac{1}{2} ks^2$$

where $k = \frac{72\epsilon}{r_0^2} = \frac{72(4.65 \text{ eV})}{(0.305 \text{ nm})^2} = 3599 \text{ eV/nm}^2 = \boxed{576 \text{ N/m}}$

P43.5 At the boiling or condensation temperature, $k_B T \approx 10^{-3} \text{ eV} = 10^{-3} (1.6 \times 10^{-19} \text{ J})$

$$T \approx \frac{1.6 \times 10^{-22} \text{ J}}{1.38 \times 10^{-23} \text{ J/K}} \approx \boxed{\sim 10 \text{ K}}$$

Section 43.2 Energy States and Spectra of Molecules

***P43.6** (a) With r representing the distance of each atom from the center of mass, the moment of inertia is

$$mr^2 + mr^2 = 2(1.67 \times 10^{-27} \text{ kg}) \left(\frac{0.75 \times 10^{-10} \text{ m}}{2} \right)^2 = 4.70 \times 10^{-48} \text{ kg} \cdot \text{m}^2$$

The rotational energy is $E_{\text{rot}} = \frac{\hbar^2}{2I} J(J+1)$ or it is zero for $J=0$ and for $J=1$ it is

$$\frac{\hbar^2 1(2)}{4\pi^2 2I} = \frac{(6.626 \times 10^{-34} \text{ J} \cdot \text{s})^2}{4\pi^2 (4.70 \times 10^{-48} \text{ kg} \cdot \text{m}^2)} \left(\frac{1 \text{ eV}}{1.6 \times 10^{-19} \text{ J}} \right) = \boxed{0.0148 \text{ eV}}$$

$$(b) \quad \lambda = \frac{c}{f} = \frac{ch}{E} = \frac{(2.998 \times 10^8 \text{ m/s})(6.626 \times 10^{-34} \text{ J} \cdot \text{s})}{0.0148 \text{ eV}} \frac{1 \text{ eV}}{1.602 \times 10^{-19} \text{ J}} = \frac{1240 \text{ eV} \cdot \text{nm}}{0.0148 \text{ eV}} = \boxed{83.8 \mu\text{m}}$$

P43.7
$$\mu = \frac{m_1 m_2}{m_1 + m_2} = \frac{132.9(126.9)}{132.9 + 126.9} (1.66 \times 10^{-27} \text{ kg}) = 1.08 \times 10^{-25} \text{ kg}$$

$$I = \mu r^2 = (1.08 \times 10^{-25} \text{ kg}) (0.127 \times 10^{-9} \text{ m})^2 = 1.74 \times 10^{-45} \text{ kg} \cdot \text{m}^2$$

$$(a) \quad E = \frac{1}{2} I \omega^2 = \frac{(I\omega)^2}{2I} = \frac{J(J+1)\hbar^2}{2I}$$

$$J=0 \text{ gives } E=0$$

$$J=1 \text{ gives } E = \frac{\hbar^2}{I} = \frac{(6.626 \times 10^{-34} \text{ J} \cdot \text{s})^2}{4\pi^2 (1.74 \times 10^{-45} \text{ kg} \cdot \text{m}^2)} = 6.41 \times 10^{-24} \text{ J} = \boxed{40.0 \mu\text{eV}}$$

$$hf = 6.41 \times 10^{-24} \text{ J} - 0 \text{ gives } f = \boxed{9.66 \times 10^9 \text{ Hz}}$$

$$(b) \quad f = \frac{E_1}{h} = \frac{\hbar^2}{hI} = \frac{h}{4\pi^2 \mu r^2} \propto r^{-2} \quad \boxed{\text{If } r \text{ is 10\% too small, } f \text{ is 20\% too large.}}$$

***P43.8**
$$\Delta E_{\text{vib}} = \frac{h}{2\pi} \sqrt{\frac{k}{\mu}} = hf \quad \text{so} \quad k = 4\pi^2 f^2 \mu$$

$$\mu = \frac{k}{4\pi^2 f^2} = \frac{1530 \text{ N/m}}{4\pi^2 (56.3 \times 10^{12} \text{ /s})^2} = \boxed{1.22 \times 10^{-26} \text{ kg}}$$

$$\mu = \frac{m_1 m_2}{m_1 + m_2} = \frac{14.007 \text{ u} \cdot 15.999 \text{ u}}{14.007 \text{ u} + 15.999 \text{ u}} \frac{1.66 \times 10^{-27} \text{ kg}}{1 \text{ u}} = \boxed{1.24 \times 10^{-26} \text{ kg}}$$

The reduced masses agree, because the small apparent difference can be attributed to uncertainty in the data.

- P43.9** For the HCl molecule in the $J = 1$ rotational energy level, we are given $r_0 = 0.1275 \text{ nm}$.

$$E_{\text{rot}} = \frac{\hbar^2}{2I} J(J+1)$$

Taking $J = 1$, we have $E_{\text{rot}} = \frac{\hbar^2}{I} = \frac{1}{2} I \omega^2$ or $\omega = \sqrt{\frac{2\hbar^2}{I^2}} = \sqrt{2} \frac{\hbar}{I}$

The moment of inertia of the molecule is given by Equation 43.3.

$$I = \mu r_0^2 = \left(\frac{m_1 m_2}{m_1 + m_2} \right) r_0^2$$

$$I = \left[\frac{(1.01 \text{ u})(35.5 \text{ u})}{1.01 \text{ u} + 35.5 \text{ u}} \right] r_0^2 = (0.982 \text{ u})(1.66 \times 10^{-27} \text{ kg/u})(1.275 \times 10^{-10} \text{ m})^2 = 2.65 \times 10^{-47} \text{ kg} \cdot \text{m}^2$$

Therefore, $\omega = \sqrt{2} \frac{\hbar}{I} = \frac{\sqrt{2} \cdot 6.626 \times 10^{-34} \text{ J} \cdot \text{s}}{2\pi(2.65 \times 10^{-47} \text{ kg} \cdot \text{m}^2)} = \boxed{5.63 \times 10^{12} \text{ rad/s}}$

P43.10 $hf = \Delta E = \frac{\hbar^2}{2I} [2(2+1)] - \frac{\hbar^2}{2I} [1(1+1)] = \frac{\hbar^2}{2I} (4)$

$$I = \frac{4(h/2\pi)^2}{2hf} = \frac{h}{2\pi^2 f} = \frac{6.626 \times 10^{-34} \text{ J} \cdot \text{s}}{2\pi^2 (2.30 \times 10^{11} \text{ Hz})} = \boxed{1.46 \times 10^{-46} \text{ kg} \cdot \text{m}^2}$$

P43.11 $I = m_1 r_1^2 + m_2 r_2^2$ where $m_1 r_1 = m_2 r_2$ and $r_1 + r_2 = r$

Then $r_1 = \frac{m_2 r_2}{m_1}$ so $\frac{m_2 r_2}{m_1} + r_2 = r$ and $r_2 = \frac{m_1 r}{m_1 + m_2}$

Also, $r_2 = \frac{m_1 r_1}{m_2}$. Thus, $r_1 + \frac{m_1 r_1}{m_2} = r$ and $r_1 = \frac{m_2 r}{m_1 + m_2}$

$$I = m_1 \frac{m_2^2 r^2}{(m_1 + m_2)^2} + \frac{m_2 m_1^2 r^2}{(m_1 + m_2)^2} = \frac{m_1 m_2 r^2 (m_2 + m_1)}{(m_1 + m_2)^2} = \frac{m_1 m_2 r^2}{m_1 + m_2} = \boxed{\mu r^2}$$

P43.12 (a) $\mu = \frac{22.99(35.45)}{(22.99 + 35.45)} (1.66 \times 10^{-27} \text{ kg}) = 2.32 \times 10^{-26} \text{ kg}$

$$I = \mu r^2 = (2.32 \times 10^{-26} \text{ kg})(0.280 \times 10^{-9} \text{ m})^2 = \boxed{1.81 \times 10^{-45} \text{ kg} \cdot \text{m}^2}$$

(b) $\frac{hc}{\lambda} = \frac{\hbar^2}{2I} 2(2+1) - \frac{\hbar^2}{2I} 1(1+1) = \frac{3\hbar^2}{I} - \frac{\hbar^2}{I} = \frac{2\hbar^2}{I} = \frac{2h^2}{4\pi^2 I}$

$$\lambda = \frac{c 4\pi^2 I}{2h} = \frac{(3.00 \times 10^8 \text{ m/s}) 4\pi^2 (1.81 \times 10^{-45} \text{ kg} \cdot \text{m}^2)}{2(6.626 \times 10^{-34} \text{ J} \cdot \text{s})} = \boxed{1.62 \text{ cm}}$$

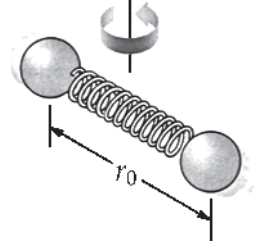


FIG. P43.9

P43.13 The energy of a rotational transition is $\Delta E = \left(\frac{\hbar^2}{I}\right)J$ where J is the rotational quantum number of the higher energy state (see Equation 43.7). We do not know J from the data. However,

$$\Delta E = \frac{hc}{\lambda} = \frac{(6.626 \times 10^{-34} \text{ J} \cdot \text{s})(3.00 \times 10^8 \text{ m/s})}{\lambda} \left(\frac{1 \text{ eV}}{1.60 \times 10^{-19} \text{ J}} \right).$$

For each observed wavelength,

λ (mm)	ΔE (eV)
0.120 4	0.010 32
0.096 4	0.012 88
0.080 4	0.015 44
0.069 0	0.018 00
0.060 4	0.020 56

The ΔE 's consistently increase by 0.002 56 eV. $E_1 = \frac{\hbar^2}{I} = 0.002 56 \text{ eV}$

$$\text{and } I = \frac{\hbar^2}{E_1} = \frac{(1.055 \times 10^{-34} \text{ J} \cdot \text{s})^2}{(0.002 56 \text{ eV})} \left(\frac{1 \text{ eV}}{1.60 \times 10^{-19} \text{ J}} \right) = \boxed{2.72 \times 10^{-47} \text{ kg} \cdot \text{m}^2}$$

For the HCl molecule, the internuclear radius is $r = \sqrt{\frac{I}{\mu}} = \sqrt{\frac{2.72 \times 10^{-47}}{1.62 \times 10^{-27}}} \text{ m} = 0.130 \text{ nm}$

***P43.14** (a) Minimum amplitude of vibration of HI is characterized by

$$\frac{1}{2}kA^2 = \frac{1}{2}\hbar\omega = \frac{h}{4\pi}\sqrt{\frac{k}{\mu}} \quad \text{so} \quad A = \sqrt{\frac{h}{2\pi}} \left(\frac{1}{k\mu} \right)^{1/4}$$

$$A = \sqrt{\frac{6.626 \times 10^{-34} \text{ J} \cdot \text{s}}{2\pi}} \left(\frac{1}{(320 \text{ N/m})(127/128)(1.66 \times 10^{-27} \text{ kg})} \right)^{1/4} = \boxed{12.1 \text{ pm}}$$

$$(b) \quad \text{For HF, } A = \sqrt{\frac{6.626 \times 10^{-34} \text{ J} \cdot \text{s}}{2\pi}} \left(\frac{1}{(970 \text{ N/m})(19/20)(1.66 \times 10^{-27} \text{ kg})} \right)^{1/4} = \boxed{9.23 \text{ pm}}$$

(c) Since HI has the smaller k , it is more weakly bound.

$$\textbf{P43.15} \quad \mu = \frac{m_1 m_2}{m_1 + m_2} = \frac{35}{36} \times 1.66 \times 10^{-27} \text{ kg} = 1.61 \times 10^{-27} \text{ kg}$$

$$\Delta E_{\text{vib}} = \hbar \sqrt{\frac{k}{\mu}} = (1.055 \times 10^{-34}) \sqrt{\frac{480}{1.61 \times 10^{-27}}} = 5.74 \times 10^{-20} \text{ J} = \boxed{0.358 \text{ eV}}$$

P43.16 (a) The reduced mass of the O_2 is

$$\mu = \frac{(16 \text{ u})(16 \text{ u})}{(16 \text{ u}) + (16 \text{ u})} = 8 \text{ u} = 8(1.66 \times 10^{-27} \text{ kg}) = 1.33 \times 10^{-26} \text{ kg}$$

The moment of inertia is then

$$I = \mu r^2 = (1.33 \times 10^{-26} \text{ kg})(1.20 \times 10^{-10} \text{ m})^2 \\ = 1.91 \times 10^{-46} \text{ kg} \cdot \text{m}^2$$

The rotational energies are
$$E_{\text{rot}} = \frac{\hbar^2}{2I} J(J+1) = \frac{(1.055 \times 10^{-34} \text{ J} \cdot \text{s})^2}{2(1.91 \times 10^{-46} \text{ kg} \cdot \text{m}^2)} J(J+1)$$

Thus
$$E_{\text{rot}} = (2.91 \times 10^{-23} \text{ J}) J(J+1)$$

And for $J = 0, 1, 2$,
$$E_{\text{rot}} = \boxed{0, 3.64 \times 10^{-4} \text{ eV}, 1.09 \times 10^{-3} \text{ eV}}$$

(b)
$$E_{\text{vib}} = \left(v + \frac{1}{2}\right) \hbar \sqrt{\frac{k}{\mu}} = \left(v + \frac{1}{2}\right) (1.055 \times 10^{-34} \text{ J} \cdot \text{s}) \sqrt{\frac{1177 \text{ N/m}}{8(1.66 \times 10^{-27} \text{ kg})}}$$

$$E_{\text{vib}} = \left(v + \frac{1}{2}\right) (3.14 \times 10^{-20} \text{ J}) \left(\frac{1 \text{ eV}}{1.60 \times 10^{-19} \text{ J}}\right) = \left(v + \frac{1}{2}\right) (0.196 \text{ eV})$$

For $v = 0, 1, 2$,
$$E_{\text{vib}} = \boxed{0.0982 \text{ eV}, 0.295 \text{ eV}, 0.491 \text{ eV}}.$$

P43.17 In Benzene, the carbon atoms are each 0.110 nm from the axis and each hydrogen atom is (0.110 + 0.100 nm) = 0.210 nm from the axis. Thus, $I = \sum mr^2$:

$$I = 6(1.99 \times 10^{-26} \text{ kg})(0.110 \times 10^{-9} \text{ m})^2 + 6(1.67 \times 10^{-27} \text{ kg})(0.210 \times 10^{-9} \text{ m})^2 \\ = 1.89 \times 10^{-45} \text{ kg} \cdot \text{m}^2$$

The allowed rotational energies are then

$$E_{\text{rot}} = \frac{\hbar^2}{2I} J(J+1) = \frac{(1.055 \times 10^{-34} \text{ J} \cdot \text{s})^2}{2(1.89 \times 10^{-45} \text{ kg} \cdot \text{m}^2)} J(J+1) = (2.95 \times 10^{-24} \text{ J}) J(J+1) \\ = (18.4 \times 10^{-6} \text{ eV}) J(J+1)$$

$$E_{\text{rot}} = \boxed{(18.4 \text{ } \mu\text{eV}) J(J+1) \text{ where } J = 0, 1, 2, 3, \dots}$$

The first five of these allowed energies are: $E_{\text{rot}} = 0, 36.9 \text{ } \mu\text{eV}, 111 \text{ } \mu\text{eV}, 221 \text{ } \mu\text{eV}$, and $369 \text{ } \mu\text{eV}$.

P43.18 We carry extra digits through the solution because part (c) involves the subtraction of two close numbers. The longest wavelength corresponds to the smallest energy difference between the rotational energy levels. It is between $J = 0$ and $J = 1$, namely $\frac{\hbar^2}{I}$

$$\lambda = \frac{hc}{\Delta E_{\min}} = \frac{hc}{\hbar^2/I} = \frac{4\pi^2 Ic}{h}. \text{ If } \mu \text{ is the reduced mass, then}$$

$$I = \mu r^2 = \mu (0.12746 \times 10^{-9} \text{ m})^2 = (1.624605 \times 10^{-20} \text{ m}^2) \mu \quad (1)$$

$$\text{Therefore } \lambda = \frac{4\pi^2 (1.624605 \times 10^{-20} \text{ m}^2) \mu (2.997925 \times 10^8 \text{ m/s})}{6.626075 \times 10^{-34} \text{ J} \cdot \text{s}} = (2.901830 \times 10^{23} \text{ m/kg}) \mu$$

$$(a) \quad \mu_{35} = \frac{(1.007825 \text{ u})(34.968853 \text{ u})}{1.007825 \text{ u} + 34.968853 \text{ u}} = 0.979593 \text{ u} = 1.626653 \times 10^{-27} \text{ kg}$$

$$\text{From (1): } \lambda_{35} = (2.901830 \times 10^{23} \text{ m/kg})(1.626653 \times 10^{-27} \text{ kg}) = \boxed{472 \text{ } \mu\text{m}}$$

$$(b) \quad \mu_{37} = \frac{(1.007825 \text{ u})(36.965903 \text{ u})}{1.007825 \text{ u} + 36.965903 \text{ u}} = 0.981077 \text{ u} = 1.629118 \times 10^{-27} \text{ kg}$$

$$\text{From (1): } \lambda_{37} = (2.901830 \times 10^{23} \text{ m/kg})(1.629118 \times 10^{-27} \text{ kg}) = \boxed{473 \text{ } \mu\text{m}}$$

$$(c) \quad \lambda_{37} - \lambda_{35} = 472.7424 \text{ } \mu\text{m} - 472.0270 \text{ } \mu\text{m} = \boxed{0.715 \text{ } \mu\text{m}}$$

P43.19 We find an average spacing between peaks by counting 22 gaps between $7.96 \times 10^{13} \text{ Hz}$ and $9.24 \times 10^{13} \text{ Hz}$:

$$\Delta f = \frac{(9.24 - 7.96)10^{13} \text{ Hz}}{22} = 0.0582 \times 10^{13} \text{ Hz} = \frac{1}{h} \left(\frac{\hbar^2}{4\pi^2 I} \right)$$

$$I = \frac{h}{4\pi^2 \Delta f} = \frac{6.63 \times 10^{-34} \text{ J} \cdot \text{s}}{4\pi^2 (5.82 \times 10^{11} / \text{s})} = \boxed{2.9 \times 10^{-47} \text{ kg} \cdot \text{m}^2}$$

P43.20 We carry extra digits through the solution because the given wavelengths are close together.

$$\begin{aligned}
 \text{(a)} \quad E_{v,J} &= \left(v + \frac{1}{2}\right)hf + \frac{\hbar^2}{2I}J(J+1) \\
 \therefore E_{00} &= \frac{1}{2}hf, \quad E_{11} = \frac{3}{2}hf + \frac{\hbar^2}{I}, \quad E_{02} = \frac{1}{2}hf + \frac{3\hbar^2}{I} \\
 \therefore E_{11} - E_{00} &= hf + \frac{\hbar^2}{I} = \frac{hc}{\lambda} = \frac{(6.626\,075 \times 10^{-34} \text{ J}\cdot\text{s})(2.997\,925 \times 10^8 \text{ m/s})}{2.211\,2 \times 10^{-6} \text{ m}} \\
 \therefore hf + \frac{\hbar^2}{I} &= 8.983\,573 \times 10^{-20} \text{ J} \tag{1}
 \end{aligned}$$

$$\begin{aligned}
 E_{11} - E_{02} &= hf - \frac{2\hbar^2}{I} = \frac{hc}{\lambda} = \frac{(6.626\,075 \times 10^{-34} \text{ J}\cdot\text{s})(2.997\,925 \times 10^8 \text{ m/s})}{2.405\,4 \times 10^{-6} \text{ m}} \\
 \therefore hf - \frac{2\hbar^2}{I} &= 8.258\,284 \times 10^{-20} \text{ J} \tag{2}
 \end{aligned}$$

$$\text{Subtract (2) from (1): } \frac{3\hbar^2}{I} = 7.252\,89 \times 10^{-21} \text{ J}$$

$$\therefore I = \frac{3(1.054\,573 \times 10^{-34} \text{ J}\cdot\text{s})^2}{7.252\,89 \times 10^{-21} \text{ J}} = \boxed{4.60 \times 10^{-48} \text{ kg}\cdot\text{m}^2}$$

(b) From (1):

$$\begin{aligned}
 f &= \frac{8.983\,573 \times 10^{-20} \text{ J}}{6.626\,075 \times 10^{-34} \text{ J}\cdot\text{s}} - \frac{(1.054\,573 \times 10^{-34} \text{ J}\cdot\text{s})^2}{(4.600\,060 \times 10^{-48} \text{ kg}\cdot\text{m}^2)(6.626\,075 \times 10^{-34} \text{ J}\cdot\text{s})} \\
 &= \boxed{1.32 \times 10^{14} \text{ Hz}}
 \end{aligned}$$

(c) $I = \mu r^2$, where μ is the reduced mass:

$$\mu = \frac{1}{2}m_H = \frac{1}{2}(1.007\,825\text{u}) = 8.367\,669 \times 10^{-28} \text{ kg}$$

$$\text{So } r = \sqrt{\frac{I}{\mu}} = \sqrt{\frac{4.600\,060 \times 10^{-48} \text{ kg}\cdot\text{m}^2}{8.367\,669 \times 10^{-28} \text{ kg}}} = \boxed{0.074\,1 \text{ nm}}.$$

P43.21 The emission energies are the same as the absorption energies, but the final state must be below ($v = 1, J = 0$). The transition must satisfy $\Delta J = \pm 1$, so it must end with $J = 1$. To be lower in energy, it must be ($v = 0, J = 1$). The emitted photon energy is therefore

$$\begin{aligned}
 hf_{\text{photon}} &= (E_{\text{vib}}|_{v=1} + E_{\text{rot}}|_{J=0}) - (E_{\text{vib}}|_{v=0} + E_{\text{rot}}|_{J=1}) = (E_{\text{vib}}|_{v=1} - E_{\text{vib}}|_{v=0}) - (E_{\text{rot}}|_{J=1} - E_{\text{rot}}|_{J=0}) \\
 hf_{\text{photon}} &= hf_{\text{vib}} - hf_{\text{rot}}
 \end{aligned}$$

$$\text{Thus, } f_{\text{photon}} = f_{\text{vib}} - f_{\text{rot}} = 6.42 \times 10^{13} \text{ Hz} - 1.15 \times 10^{11} \text{ Hz} = \boxed{6.41 \times 10^{13} \text{ Hz}}.$$

P43.22 The moment of inertia about the molecular axis is $I_x = \frac{2}{5}mr^2 + \frac{2}{5}mr^2 = \frac{4}{5}m(2.00 \times 10^{-15} \text{ m})^2$.

$$\text{The moment of inertia about a perpendicular axis is } I_y = m\left(\frac{R}{2}\right)^2 + m\left(\frac{R}{2}\right)^2 = \frac{m}{2}(2.00 \times 10^{-10} \text{ m})^2.$$

The allowed rotational energies are $E_{\text{rot}} = \left(\frac{\hbar^2}{2I}\right)J(J+1)$, so the energy of the first excited state is

$$E_1 = \frac{\hbar^2}{I}. \text{ The ratio is therefore}$$

$$\frac{E_{1,x}}{E_{1,y}} = \frac{(\hbar^2/I_x)}{(\hbar^2/I_y)} = \frac{I_y}{I_x} = \frac{(1/2)m(2.00 \times 10^{-10} \text{ m})^2}{(4/5)m(2.00 \times 10^{-15} \text{ m})^2} = \frac{5}{8}(10^5)^2 = \boxed{6.25 \times 10^9}$$

Section 43.3 **Bonding in Solids**

P43.23 $U = -\frac{\alpha k_e e^2}{r_0} \left(1 - \frac{1}{m}\right) = -(1.7476)(8.99 \times 10^9) \frac{(1.60 \times 10^{-19})^2}{(0.281 \times 10^{-9})} \left(1 - \frac{1}{8}\right) = -1.25 \times 10^{-18} \text{ J} = \boxed{-7.84 \text{ eV}}$

P43.24 Consider a cubical salt crystal of edge length 0.1 mm.

The number of atoms is $\left(\frac{10^{-4} \text{ m}}{0.261 \times 10^{-9} \text{ m}}\right)^3 \boxed{\sim 10^{17}}$

This number of salt crystals would have volume $(10^{-4} \text{ m})^3 \left(\frac{10^{-4} \text{ m}}{0.261 \times 10^{-9} \text{ m}}\right)^3 \boxed{\sim 10^5 \text{ m}^3}$

If it is cubic, it has edge length 40 m.

P43.25 $U = -\frac{k_e e^2}{r} - \frac{k_e e^2}{r} + \frac{k_e e^2}{2r} + \frac{k_e e^2}{2r} - \frac{k_e e^2}{3r} - \frac{k_e e^2}{3r} + \frac{k_e e^2}{4r} + \frac{k_e e^2}{4r} - \dots$
 $= -\frac{2k_e e^2}{r} \left(1 - \frac{1}{2} + \frac{1}{3} - \frac{1}{4} + \dots\right)$

But, $\ln(1+x) = 1 - \frac{x^2}{2} + \frac{x^3}{3} - \frac{x^4}{4} + \dots$

so, $U = -\frac{2k_e e^2}{r} \ln 2$, or $\boxed{U = -k_e \alpha \frac{e^2}{r} \text{ where } \alpha = 2 \ln 2}$

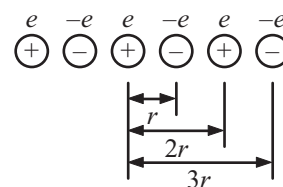


FIG. P43.25

P43.26 Visualize a K^+ ion at the center of each shaded cube, a Cl^- ion at the center of each white one.

The distance ab is $\sqrt{2}(0.314 \text{ nm}) = \boxed{0.444 \text{ nm}}$

Distance ac is $2(0.314 \text{ nm}) = \boxed{0.628 \text{ nm}}$

Distance ad is $\sqrt{2^2 + (\sqrt{2})^2}(0.314 \text{ nm}) = \boxed{0.769 \text{ nm}}$

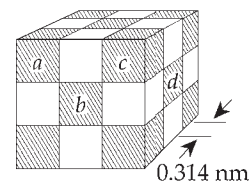


FIG. P43.26

Section 43.4 **Free-Electron Theory of Metals**Section 43.5 **Band Theory of Solids**

P43.27 The density of conduction electrons n is given by $E_F = \frac{h^2}{2m} \left(\frac{3n}{8\pi}\right)^{2/3}$

or $n_e = \frac{8\pi}{3} \left(\frac{2mE_F}{h^2}\right)^{3/2} = \frac{8\pi}{3} \frac{[2(9.11 \times 10^{-31} \text{ kg})(5.48)(1.60 \times 10^{-19} \text{ J})]^{3/2}}{(6.626 \times 10^{-34} \text{ J}\cdot\text{s})^3} = 5.80 \times 10^{28} \text{ m}^{-3}$

The number-density of silver atoms is

$$n_{\text{Ag}} = (10.6 \times 10^3 \text{ kg/m}^3) \left(\frac{1 \text{ atom}}{108 \text{ u}}\right) \left(\frac{1 \text{ u}}{1.66 \times 10^{-27} \text{ kg}}\right) = 5.91 \times 10^{28} \text{ m}^{-3}$$

So an average atom contributes $\frac{5.80}{5.91} = \boxed{0.981 \text{ electron to the conduction band}}$.

- *P43.28** (a) The Fermi energy is proportional to the spatial concentration of free electrons to the two-thirds power.

$$(b) \quad E_F = \frac{h^2}{2m} \left(\frac{3n_e}{8\pi} \right)^{2/3} = \frac{(6.626 \times 10^{-34} \text{ J}\cdot\text{s})^2}{2(9.11 \times 10^{-31} \text{ kg})(1.60 \times 10^{-19} \text{ J/eV})} \left(\frac{3}{8\pi} \right)^{2/3} n_e^{2/3} \text{ becomes}$$

$$E_F = (3.65 \times 10^{-19}) n_e^{2/3} \text{ eV with } n \text{ measured in electrons/m}^3.$$

- (c) Copper has the greater concentration of free electrons by a factor of $8.49 \times 10^{28} / 1.40 \times 10^{28} = 6.06$.
Copper has the greater Fermi energy by a factor of $7.05 \text{ eV} / 2.12 \text{ eV} = 3.33$. This behavior agrees with the proportionality because $6.06^{2/3} = 3.33$.

P43.29 (a) $\frac{1}{2}mv^2 = 7.05 \text{ eV}$

$$v = \sqrt{\frac{2(7.05 \text{ eV})(1.60 \times 10^{-19} \text{ J/eV})}{9.11 \times 10^{-31} \text{ kg}}} = \boxed{1.57 \times 10^6 \text{ m/s}}$$

- (b) Larger than 10^{-4} m/s by ten orders of magnitude. However, the energy of an electron at room temperature is typically $k_B T = \frac{1}{40} \text{ eV}$.

- *P43.30** The occupation probability is

$$f(E) = \frac{1}{e^{(E-E_F)/k_B T} + 1} = \frac{1}{e^{(0.99 E_F - E_F)/k_B T} + 1} = \frac{1}{\exp[-0.01(7.05 \text{ eV})(1.6 \times 10^{-19} \text{ J/eV}) / (1.38 \times 10^{-23} \text{ J/K})(300 \text{ K})] + 1} = \frac{1}{e^{-2.72} + 1} = \boxed{0.938}$$

***P43.31** (a) $E_{av} = \frac{3}{5} E_F = 0.6(7.05 \text{ eV}) = \boxed{4.23 \text{ eV}}$

- (b) The average energy of a molecule in an ideal gas is $\frac{3}{2} k_B T$ so we have

$$T = \frac{2}{3} \frac{4.23 \text{ eV}}{1.38 \times 10^{-23} \text{ J/K}} \frac{1.6 \times 10^{-19} \text{ J}}{1 \text{ eV}} = \boxed{3.27 \times 10^4 \text{ K}}$$

- P43.32** For sodium, $M = 23.0 \text{ g/mol}$ and $\rho = 0.971 \text{ g/cm}^3$.

$$(a) \quad n_e = \frac{N_A \rho}{M} = \frac{(6.02 \times 10^{23} \text{ electrons/mol})(0.971 \text{ g/cm}^3)}{23.0 \text{ g/mol}}$$

$$n_e = 2.54 \times 10^{22} \text{ electrons/cm}^3 = \boxed{2.54 \times 10^{28} \text{ electrons/m}^3}$$

$$(b) \quad E_F = \left(\frac{h^2}{2m} \right) \left(\frac{3n_e}{8\pi} \right)^{2/3} = \frac{(6.626 \times 10^{-34} \text{ J}\cdot\text{s})^2}{2(9.11 \times 10^{-31} \text{ kg})} \left[\frac{3(2.54 \times 10^{28} \text{ m}^{-3})}{8\pi} \right]^{2/3} = 5.05 \times 10^{-19} \text{ J} = \boxed{3.15 \text{ eV}}$$

- P43.33** Taking $E_F = 5.48 \text{ eV}$ for sodium at 800 K ,

$$f = \left[e^{(E-E_F)/k_B T} + 1 \right]^{-1} = 0.950$$

$$e^{(E-E_F)/k_B T} = \frac{1}{0.950} - 1 = 0.0526$$

$$\frac{E-E_F}{k_B T} = \ln(0.0526) = -2.94$$

$$E-E_F = -2.94 \frac{(1.38 \times 10^{-23} \text{ J})(800 \text{ K})}{1.60 \times 10^{-19} \text{ J/eV}} = -0.203 \text{ eV or } \boxed{E = 5.28 \text{ eV}}$$

- P43.34** The melting point of silver is 1 234 K. Its Fermi energy at 300 K is 5.48 eV. The approximate fraction of electrons excited is

$$\frac{k_B T}{E_F} = \frac{(1.38 \times 10^{-23} \text{ J/K})(1\,234 \text{ K})}{(5.48 \text{ eV})(1.60 \times 10^{-19} \text{ J/eV})} \approx \boxed{2\%}$$

P43.35 $E_{\text{av}} = \frac{1}{n_e} \int_0^{\infty} EN(E) dE$

At $T = 0$, $N(E) = 0$ for $E > E_F$

Since $f(E) = 1$ for $E < E_F$ and $f(E) = 0$ for $E > E_F$,

we can take $N(E) = CE^{1/2} = \frac{8\sqrt{2}\pi m_e^{3/2}}{h^3} E^{1/2}$

$$E_{\text{av}} = \frac{1}{n_e} \int_0^{E_F} CE^{3/2} dE = \frac{C}{n_e} \int_0^{E_F} E^{3/2} dE = \frac{2C}{5n_e} E_F^{5/2}$$

But from Equation 43.25, $\frac{C}{n_e} = \frac{3}{2} E_F^{-3/2}$, so that $E_{\text{av}} = \left(\frac{2}{5}\right) \left(\frac{3}{2} E_F^{-3/2}\right) E_F^{5/2} = \boxed{\frac{3}{5} E_F}$

P43.36 $d = 1.00 \text{ mm}$, so $V = (1.00 \times 10^{-3} \text{ m})^3 = 1.00 \times 10^{-9} \text{ m}^3$

The density of states is $g(E) = CE^{1/2} = \frac{8\sqrt{2}\pi m^{3/2}}{h^3} E^{1/2}$

or $g(E) = \frac{8\sqrt{2}\pi (9.11 \times 10^{-31} \text{ kg})^{3/2}}{(6.626 \times 10^{-34} \text{ J}\cdot\text{s})^3} \sqrt{(4.00 \text{ eV})(1.60 \times 10^{-19} \text{ J/eV})}$

$$g(E) = 8.50 \times 10^{46} \text{ m}^{-3} \cdot \text{J}^{-1} = 1.36 \times 10^{28} \text{ m}^{-3} \cdot \text{eV}^{-1}$$

So, the total number of electrons is

$$N = [g(E)](\Delta E)V = (1.36 \times 10^{28} \text{ m}^{-3} \cdot \text{eV}^{-1})(0.0250 \text{ eV})(1.00 \times 10^{-9} \text{ m}^3)$$

$$= \boxed{3.40 \times 10^{17} \text{ electrons}}$$

- *P43.37** (a) The density of states at energy E is

$$g(E) = CE^{1/2}$$

Hence, the required ratio is

$$\frac{g(8.50 \text{ eV})}{g(7.00 \text{ eV})} = \frac{C(8.50)^{1/2}}{C(7.00)^{1/2}} = \boxed{1.10}$$

- (b) From Equation 43.22, the number of occupied states having energy E is

$$N(E) = \frac{CE^{1/2}}{e^{(E-E_F)/k_B T} + 1}$$

Hence, the required ratio is

$$\frac{N(8.50 \text{ eV})}{N(7.00 \text{ eV})} = \frac{(8.50)^{1/2}}{(7.00)^{1/2}} \left[\frac{e^{(7.00-7.00)/k_B T} + 1}{e^{(8.50-7.00)/k_B T} + 1} \right]$$

At $T = 300 \text{ K}$, $k_B T = 4.14 \times 10^{-21} \text{ J} = 0.0259 \text{ eV}$,

$$\frac{N(8.50 \text{ eV})}{N(7.00 \text{ eV})} = \frac{(8.50)^{1/2}}{(7.00)^{1/2}} \left[\frac{2.00}{e^{(1.50)/0.0259} + 1} \right]$$

And

$$\frac{N(8.50 \text{ eV})}{N(7.00 \text{ eV})} = \boxed{1.47 \times 10^{-25}}$$

This result is vastly smaller than that in part (a). We conclude that very few states well above the Fermi energy are occupied at room temperature.

P43.38 Consider first the wave function in x . At $x = 0$ and $x = L$, $\psi = 0$.

$$\text{Therefore, } \sin k_x L = 0 \quad \text{and} \quad k_x L = \pi, 2\pi, 3\pi, \dots$$

$$\text{Similarly, } \sin k_y L = 0 \quad \text{and} \quad k_y L = \pi, 2\pi, 3\pi, \dots$$

$$\sin k_z L = 0 \quad \text{and} \quad k_z L = \pi, 2\pi, 3\pi, \dots$$

$$\psi = A \sin\left(\frac{n_x \pi x}{L}\right) \sin\left(\frac{n_y \pi y}{L}\right) \sin\left(\frac{n_z \pi z}{L}\right)$$

$$\text{From } \frac{\partial^2 \psi}{\partial x^2} + \frac{\partial^2 \psi}{\partial y^2} + \frac{\partial^2 \psi}{\partial z^2} = \frac{2m_e}{\hbar^2} (U - E) \psi, \quad \text{we have inside the box, where } U = 0,$$

$$\left(-\frac{n_x^2 \pi^2}{L^2} - \frac{n_y^2 \pi^2}{L^2} - \frac{n_z^2 \pi^2}{L^2} \right) \psi = \frac{2m_e}{\hbar^2} (-E) \psi \quad \boxed{E = \frac{\hbar^2 \pi^2}{2m_e L^2} (n_x^2 + n_y^2 + n_z^2) \quad n_x, n_y, n_z = 1, 2, 3, \dots}$$

Outside the box we require $\psi = 0$.

$$\text{The minimum energy state inside the box is } n_x = n_y = n_z = 1, \text{ with } E = \frac{3\hbar^2 \pi^2}{2m_e L^2}$$

Section 43.6 Electrical Conduction in Metals, Insulators, and Semiconductors

P43.39 (a) $E_g = 1.14 \text{ eV}$ for Si

$$hf = 1.14 \text{ eV} = (1.14 \text{ eV})(1.60 \times 10^{-19} \text{ J/eV}) = 1.82 \times 10^{-19} \text{ J} \quad \text{so} \quad f \geq \boxed{2.75 \times 10^{14} \text{ Hz}}$$

$$(b) \quad c = \lambda f; \quad \lambda = \frac{c}{f} = \frac{3.00 \times 10^8 \text{ m/s}}{2.75 \times 10^{14} \text{ Hz}} = 1.09 \times 10^{-6} \text{ m} = \boxed{1.09 \mu\text{m}} \quad (\text{in the infrared region})$$

P43.40 Photons of energy greater than 2.42 eV will be absorbed. This means wavelength shorter than

$$\lambda = \frac{hc}{E} = \frac{(6.626 \times 10^{-34} \text{ J}\cdot\text{s})(3.00 \times 10^8 \text{ m/s})}{2.42 \times 1.60 \times 10^{-19} \text{ J}} = 514 \text{ nm}$$

All the hydrogen Balmer lines except for the red line at 656 nm will be absorbed.

***P43.41** If $\lambda \leq 1.00 \times 10^{-6} \text{ m}$, then photons of sunlight have energy

$$E \geq \frac{hc}{\lambda_{\max}} = \frac{(6.626 \times 10^{-34} \text{ J}\cdot\text{s})(3.00 \times 10^8 \text{ m/s})}{1.00 \times 10^{-6} \text{ m}} \left(\frac{1 \text{ eV}}{1.60 \times 10^{-19} \text{ J}} \right) = 1.24 \text{ eV}$$

Thus, the energy gap for the collector material should be $\boxed{E_g \leq 1.24 \text{ eV}}$. Since Si has an energy gap $E_g \approx 1.14 \text{ eV}$, it can absorb nearly all of the photons in sunlight. Therefore,

Si is an appropriate material for a solar collector.

$$\textbf{P43.42} \quad E_g = \frac{hc}{\lambda} = \frac{(6.626 \times 10^{-34} \text{ J}\cdot\text{s})(3.00 \times 10^8 \text{ m/s})}{650 \times 10^{-9} \text{ m}} \text{ J} \approx \boxed{1.91 \text{ eV}}$$

P43.43 If the photon energy is 5.5 eV or higher, the diamond window will absorb. Here,

$$(hf)_{\max} = \frac{hc}{\lambda_{\min}} = 5.5 \text{ eV}; \quad \lambda_{\min} = \frac{hc}{5.5 \text{ eV}} = \frac{(6.626 \times 10^{-34} \text{ J}\cdot\text{s})(3.00 \times 10^8 \text{ m/s})}{(5.5 \text{ eV})(1.60 \times 10^{-19} \text{ J/eV})}$$

$$\lambda_{\min} = 2.26 \times 10^{-7} \text{ m} = \boxed{226 \text{ nm}}$$

P43.44 In the Bohr model we replace k_e by $\frac{k_e}{\kappa}$ and m_e by m^* . Then the radius of the first Bohr orbit,

$$a_0 = \frac{\hbar^2}{m_e k_e e^2} \text{ in hydrogen, changes to}$$

$$a' = \frac{\hbar^2 \kappa}{m^* k_e e^2} = \left(\frac{m_e}{m^*}\right) \kappa \frac{\hbar^2}{m_e k_e e^2} = \left(\frac{m_e}{m^*}\right) \kappa a_0 = \left(\frac{m_e}{0.220 m_e}\right) 11.7 (0.0529 \text{ nm}) = \boxed{2.81 \text{ nm}}$$

The energy levels are in hydrogen $E_n = -\frac{k_e e^2}{2a_0} \frac{1}{n^2}$ and here

$$E'_n = -\frac{k_e e^2}{\kappa 2a'} \frac{1}{n^2} = -\frac{k_e e^2}{\kappa 2\left(\frac{m_e}{m^*}\right) \kappa a_0} = -\left(\frac{m^*}{m_e}\right) \frac{E_n}{\kappa^2}$$

$$\text{For } n=1, \quad E'_1 = -0.220 \frac{13.6 \text{ eV}}{11.7^2} = \boxed{-0.0219 \text{ eV}}.$$

Section 43.7 Semiconductor Devices

P43.45 $I = I_0 \left(e^{e(\Delta V)/k_B T} - 1 \right)$ Thus, $e^{e(\Delta V)/k_B T} = 1 + \frac{I}{I_0}$

and

$$\Delta V = \frac{k_B T}{e} \ln \left(1 + \frac{I}{I_0} \right)$$

At $T = 300 \text{ K}$,
$$\Delta V = \frac{(1.38 \times 10^{-23} \text{ J/K})(300 \text{ K})}{1.60 \times 10^{-19} \text{ C}} \ln \left(1 + \frac{I}{I_0} \right) = (25.9 \text{ mV}) \ln \left(1 + \frac{I}{I_0} \right)$$

(a) If $I = 9.00 I_0$, $\Delta V = (25.9 \text{ mV}) \ln(10.0) = \boxed{59.5 \text{ mV}}$

(b) If $I = -0.900 I_0$, $\Delta V = (25.9 \text{ mV}) \ln(0.100) = \boxed{-59.5 \text{ mV}}$

The basic idea behind a semiconductor device is that a large current or charge can be controlled by a small control voltage.

P43.46 The voltage across the diode is about 0.6 V. The voltage drop across the resistor is $(0.025 \text{ A})(150 \Omega) = 3.75 \text{ V}$. Thus, $\mathcal{E} - 0.6 \text{ V} - 3.8 \text{ V} = 0$ and $\mathcal{E} = \boxed{4.4 \text{ V}}$.

P43.47 First, we evaluate I_0 in $I = I_0 \left(e^{e(\Delta V)/k_B T} - 1 \right)$, given that $I = 200 \text{ mA}$ when $\Delta V = 100 \text{ mV}$ and $T = 300 \text{ K}$.

$$\frac{e(\Delta V)}{k_B T} = \frac{(1.60 \times 10^{-19} \text{ C})(0.100 \text{ V})}{(1.38 \times 10^{-23} \text{ J/K})(300 \text{ K})} = 3.86 \text{ so } I_0 = \frac{I}{e^{e(\Delta V)/k_B T} - 1} = \frac{200 \text{ mA}}{e^{3.86} - 1} = 4.28 \text{ mA}$$

If $\Delta V = -100 \text{ mV}$, $\frac{e(\Delta V)}{k_B T} = -3.86$; and the current will be

$$I = I_0 \left(e^{e(\Delta V)/k_B T} - 1 \right) = (4.28 \text{ mA}) \left(e^{-3.86} - 1 \right) = \boxed{-4.19 \text{ mA}}$$

P43.48 (a) The currents to be plotted are

$$I_D = (10^{-6} \text{ A})(e^{\Delta V/0.025 \text{ V}} - 1),$$

$$I_W = \frac{2.42 \text{ V} - \Delta V}{745 \Omega}$$

The two graphs intersect at $\Delta V = 0.200 \text{ V}$. The currents are then

$$I_D = (10^{-6} \text{ A})(e^{0.200 \text{ V}/0.025 \text{ V}} - 1) = 2.98 \text{ mA}$$

$$I_W = \frac{2.42 \text{ V} - 0.200 \text{ V}}{745 \Omega} = 2.98 \text{ mA. They agree to three digits.}$$

$$\therefore I_D = I_W = \boxed{2.98 \text{ mA}}$$

$$(b) \frac{\Delta V}{I_D} = \frac{0.200 \text{ V}}{2.98 \times 10^{-3} \text{ A}} = \boxed{67.1 \Omega}$$

$$(c) \frac{d(\Delta V)}{dI_D} = \left[\frac{dI_D}{d(\Delta V)} \right]^{-1} = \left[\frac{10^{-6} \text{ A}}{0.025 \text{ V}} e^{0.200 \text{ V}/0.025 \text{ V}} \right]^{-1} = \boxed{8.39 \Omega}$$

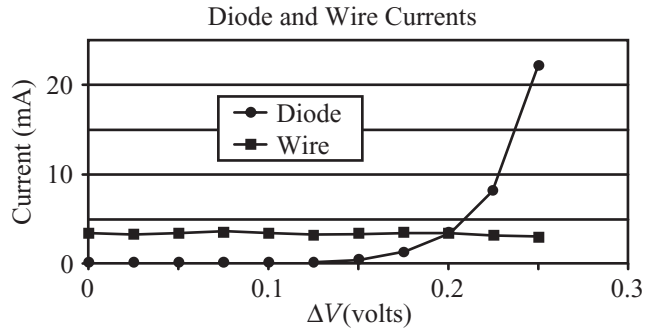


FIG. P43.48

Section 43.8 Superconductivity

P43.49 By Faraday's law (from Chapter 32) $\frac{\Delta \Phi_B}{\Delta t} = L \frac{\Delta I}{\Delta t} = A \frac{\Delta B}{\Delta t}$

$$\text{Thus, } \Delta I = \frac{A(\Delta B)}{L} = \frac{\pi(0.0100 \text{ m})^2(0.0200 \text{ T})}{3.10 \times 10^{-8} \text{ H}} = \boxed{203 \text{ A}}$$

The direction of the induced current is such as to maintain the B -field through the ring.

***P43.50** (a) In the definition of resistance $\Delta V = IR$, if R is zero then $\Delta V = 0$ for any value of current.

(b) The graph shows a direct proportionality with resistance given by the reciprocal of the slope:

$$\text{Slope} = \frac{1}{R} = \frac{\Delta I}{\Delta V} = \frac{(155 - 57.8) \text{ mA}}{(3.61 - 1.356) \text{ mV}} = 43.1 \Omega^{-1}$$

$$R = \boxed{0.0232 \Omega}$$

(c) Expulsion of magnetic flux and therefore fewer current-carrying paths could explain the decrease in current.

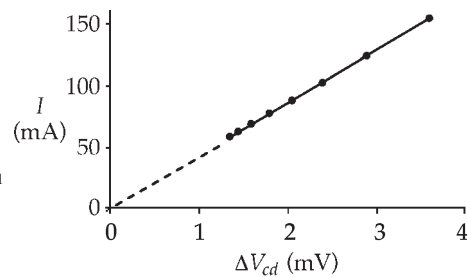


FIG. P43.50

P43.51 (a) See the figure at right.

(b) For a surface current around the outside of the cylinder as shown,

$$B = \frac{N\mu_0 I}{\ell} \quad \text{or} \quad NI = \frac{B\ell}{\mu_0} = \frac{(0.540 \text{ T})(2.50 \times 10^{-2} \text{ m})}{(4\pi \times 10^{-7} \text{ T} \cdot \text{m/A})} = \boxed{10.7 \text{ kA}}$$

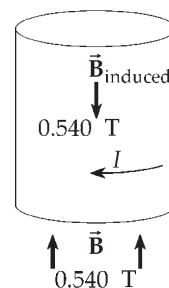


FIG. P43.51

Additional Problems

P43.52 For the N_2 molecule, $k = 2\,297 \text{ N/m}$, $m = 2.32 \times 10^{-26} \text{ kg}$, $r = 1.20 \times 10^{-10} \text{ m}$, $\mu = \frac{m}{2}$

$$\omega = \sqrt{\frac{k}{\mu}} = 4.45 \times 10^{14} \text{ rad/s}, \quad I = \mu r^2 = (1.16 \times 10^{-26} \text{ kg})(1.20 \times 10^{-10} \text{ m})^2 = 1.67 \times 10^{-46} \text{ kg} \cdot \text{m}^2$$

For a rotational state sufficient to allow a transition to the first excited vibrational state,

$$\frac{\hbar^2}{2I} J(J+1) = \hbar\omega \quad \text{so} \quad J(J+1) = \frac{2I\omega}{\hbar} = \frac{2(1.67 \times 10^{-46})(4.45 \times 10^{14})}{1.055 \times 10^{-34}} = 1\,410.$$

Thus $J = 37$.

***P43.53** (a) Since the interatomic potential is the same for both molecules, the spring constant is the same.

$$\text{Then } f = \frac{1}{2\pi} \sqrt{\frac{k}{\mu}} \quad \text{where } \mu_{12} = \frac{(12 \text{ u})(16 \text{ u})}{12 \text{ u} + 16 \text{ u}} = 6.86 \text{ u} \quad \text{and} \quad \mu_{14} = \frac{(14 \text{ u})(16 \text{ u})}{14 \text{ u} + 16 \text{ u}} = 7.47 \text{ u}.$$

Therefore,

$$f_{14} = \frac{1}{2\pi} \sqrt{\frac{k}{\mu_{14}}} = \frac{1}{2\pi} \sqrt{\frac{k}{\mu_{12}}} \left(\frac{\mu_{12}}{\mu_{14}} \right) = f_{12} \sqrt{\frac{\mu_{12}}{\mu_{14}}} = (6.42 \times 10^{13} \text{ Hz}) \sqrt{\frac{6.86 \text{ u}}{7.47 \text{ u}}} = \boxed{6.15 \times 10^{13} \text{ Hz}}$$

(b) The equilibrium distance is the same for both molecules.

$$I_{14} = \mu_{14} r^2 = \left(\frac{\mu_{14}}{\mu_{12}} \right) \mu_{12} r^2 = \left(\frac{\mu_{14}}{\mu_{12}} \right) I_{12}$$

$$I_{14} = \left(\frac{7.47 \text{ u}}{6.86 \text{ u}} \right) (1.46 \times 10^{-46} \text{ kg} \cdot \text{m}^2) = \boxed{1.59 \times 10^{-46} \text{ kg} \cdot \text{m}^2}$$

(c) The molecule can move to the $(v=1, J=9)$ state or to the $(v=1, J=11)$ state. The energy it can absorb is either

$$\Delta E = \frac{hc}{\lambda} = \left[\left(1 + \frac{1}{2} \right) \hbar f_{14} + 9(9+1) \frac{\hbar^2}{2I_{14}} \right] - \left[\left(0 - \frac{1}{2} \right) \hbar f_{14} + 10(10+1) \frac{\hbar^2}{2I_{14}} \right]$$

$$\text{or} \quad \Delta E = \frac{hc}{\lambda} = \left[\left(1 + \frac{1}{2} \right) \hbar f_{14} + 11(11+1) \frac{\hbar^2}{2I_{14}} \right] - \left[\left(0 + \frac{1}{2} \right) \hbar f_{14} + 10(10+1) \frac{\hbar^2}{2I_{14}} \right]$$

The wavelengths it can absorb are then

$$\lambda = \frac{c}{f_{14} - 10\hbar/(2\pi I_{14})} \quad \text{or} \quad \lambda = \frac{c}{f_{14} + 11\hbar/(2\pi I_{14})}$$

These are:

$$\lambda = \frac{3.00 \times 10^8 \text{ m/s}}{6.15 \times 10^{13} \text{ Hz} - [10(1.055 \times 10^{-34} \text{ J} \cdot \text{s})]/[2\pi(1.59 \times 10^{-46} \text{ kg} \cdot \text{m}^2)]} = \boxed{4.96 \mu\text{m}}$$

$$\text{and } \lambda = \frac{3.00 \times 10^8 \text{ m/s}}{6.15 \times 10^{13} \text{ Hz} + [11(1.055 \times 10^{-34} \text{ J} \cdot \text{s})]/[2\pi(1.59 \times 10^{-46} \text{ kg} \cdot \text{m}^2)]} = \boxed{4.79 \mu\text{m}}$$

P43.54 With 4 van der Waals bonds per atom pair or 2 electrons per atom, the total energy of the solid is

$$E = 2(1.74 \times 10^{-23} \text{ J/atom}) \left(\frac{6.02 \times 10^{23} \text{ atoms}}{4.00 \text{ g}} \right) = \boxed{5.23 \text{ J/g}}$$

P43.55 $\Delta E_{\max} = 4.5 \text{ eV} = \left(v + \frac{1}{2} \right) \hbar \omega$ so $\frac{(4.5 \text{ eV})(1.6 \times 10^{-19} \text{ J/eV})}{(1.055 \times 10^{-34} \text{ J} \cdot \text{s})(8.28 \times 10^{14} \text{ s}^{-1})} \geq \left(v + \frac{1}{2} \right)$
 $8.25 > 7.5$ $\boxed{v = 7}$

P43.56 Suppose it is a harmonic-oscillator potential well. Then, $\frac{1}{2} \hbar f + 4.48 \text{ eV} = \frac{3}{2} \hbar f + 3.96 \text{ eV}$ is the depth of the well below the dissociation point. We see $\hbar f = 0.520 \text{ eV}$, so the depth of the well is $\frac{1}{2} \hbar f + 4.48 \text{ eV} = \frac{1}{2} (0.520 \text{ eV}) + 4.48 \text{ eV} = \boxed{4.74 \text{ eV}}$.

P43.57 The total potential energy is given by Equation 43.17: $U_{\text{total}} = -\alpha \frac{k_e e^2}{r} + \frac{B}{r^m}$.

The total potential energy has its minimum value U_0 at the equilibrium spacing, $r = r_0$. At this

point, $\left. \frac{dU}{dr} \right|_{r=r_0} = 0$,

or $\left. \frac{dU}{dr} \right|_{r=r_0} = \frac{d}{dr} \left(-\alpha \frac{k_e e^2}{r} + \frac{B}{r^m} \right) \bigg|_{r=r_0} = \alpha \frac{k_e e^2}{r_0^2} - \frac{mB}{r_0^{m+1}} = 0$

Thus, $B = \alpha \frac{k_e e^2}{m} r_0^{m-1}$

Substituting this value of B into U_{total} , $U_0 = -\alpha \frac{k_e e^2}{r_0} + \alpha \frac{k_e e^2}{m} r_0^{m-1} \left(\frac{1}{r_0^m} \right) = \boxed{-\alpha \frac{k_e e^2}{r_0} \left(1 - \frac{1}{m} \right)}$

***P43.58** (a) The total potential energy $-\alpha \frac{k_e e^2}{r} + \frac{B}{r^m}$ has its minimum value at

the equilibrium spacing, $r = r_0$. At this point, $F = -\left. \frac{dU}{dr} \right|_{r=r_0} = 0$, or

$$F = -\left. \frac{d}{dr} \left(-\alpha \frac{k_e e^2}{r} + \frac{B}{r^m} \right) \right|_{r=r_0} = -\alpha \frac{k_e e^2}{r_0^2} + \frac{mB}{r_0^{m+1}} = 0$$

Thus, $B = \alpha \frac{k_e e^2}{m} r_0^{m-1}$.

Substituting this value of B into F , $F = -\alpha \frac{k_e e^2}{r^2} + \frac{m}{r^{m+1}} \alpha \frac{k_e e^2}{m} r_0^{m-1} = \boxed{-\alpha \frac{k_e e^2}{r^2} \left[1 - \left(\frac{r_0}{r} \right)^{m-1} \right]}$.

(b) Let $r = r_0 + x$ so $r_0 = r - x$. Then assuming x is small we have

$$\begin{aligned} F &= -\alpha \frac{k_e e^2}{r^2} \left[1 - \left(\frac{r-x}{r} \right)^{m-1} \right] = -\alpha \frac{k_e e^2}{r^2} \left[1 - \left(1 - \frac{x}{r} \right)^{m-1} \right] \approx -\alpha \frac{k_e e^2}{r^2} \left[1 - 1 + (m-1) \frac{x}{r} \right] \\ &\approx -\alpha \frac{k_e e^2}{r_0^3} (m-1)x \end{aligned}$$

This is of the form of Hooke's law with spring constant $K = k_e \alpha e^2 (m-1)/r_0^3$.

(c) Section 38.5 on electron diffraction gives the interatomic spacing in NaCl as $(0.562 \text{ nm})/2$. Other problems in this chapter give the same information, or we could calculate it from the statement in the chapter text that the ionic cohesive energy for this crystal is -7.84 eV . The stiffness constant is then

$$K = \alpha \frac{k_e e^2}{r_0^3} (m-1) = 1.7476 \frac{8.99 \times 10^9 \text{ N} \cdot \text{m}^2 (1.6 \times 10^{-19} \text{ C})^2 (8-1)}{\text{C}^2 (2.81 \times 10^{-10} \text{ m})^3} = 127 \text{ N/m}$$

The vibration frequency of a sodium ion within the crystal is

$$f = \frac{1}{2\pi} \sqrt{\frac{K}{m}} = \frac{1}{2\pi} \sqrt{\frac{127 \text{ N/m}}{23.0 \times 1.66 \times 10^{-27} \text{ kg}}} = \boxed{9.18 \text{ THz}}$$

- P43.59** (a) For equilibrium, $\frac{dU}{dx} = 0$: $\frac{d}{dx}(Ax^{-3} - Bx^{-1}) = -3Ax^{-4} + Bx^{-2} = 0$
 $x \rightarrow \infty$ describes one equilibrium position, but the stable equilibrium position is at $3Ax_0^{-2} = B$.

$$x_0 = \sqrt{\frac{3A}{B}} = \sqrt{\frac{3(0.150 \text{ eV} \cdot \text{nm}^3)}{3.68 \text{ eV} \cdot \text{nm}}} = \boxed{0.350 \text{ nm}}$$

- (b) The depth of the well is given by $U_0 = U|_{x=x_0} = \frac{A}{x_0^3} - \frac{B}{x_0} = \frac{AB^{3/2}}{3^{3/2}A^{3/2}} - \frac{BB^{1/2}}{3^{1/2}A^{1/2}}$

$$U_0 = U|_{x=x_0} = -\frac{2B^{3/2}}{3^{3/2}A^{1/2}} = -\frac{2(3.68 \text{ eV} \cdot \text{nm})^{3/2}}{3^{3/2}(0.150 \text{ eV} \cdot \text{nm}^3)^{1/2}} = \boxed{-7.02 \text{ eV}}$$

- (c) $F_x = -\frac{dU}{dx} = 3Ax^{-4} - Bx^{-2}$

To find the maximum force, we determine finite x_m such that $\left.\frac{dF}{dx}\right|_{x=x_m} = 0$.

$$\text{Thus, } \left[-12Ax^{-5} + 2Bx^{-3}\right]_{x=x_m} = 0 \text{ so that } x_m = \left(\frac{6A}{B}\right)^{1/2}$$

$$\text{Then } F_{\max} = 3A\left(\frac{B}{6A}\right)^2 - B\left(\frac{B}{6A}\right) = -\frac{B^2}{12A} = -\frac{(3.68 \text{ eV} \cdot \text{nm})^2}{12(0.150 \text{ eV} \cdot \text{nm}^3)}$$

$$\text{or } F_{\max} = -7.52 \text{ eV/nm} \left(\frac{1.60 \times 10^{-19} \text{ J}}{1 \text{ eV}}\right) \left(\frac{1 \text{ nm}}{10^{-9} \text{ m}}\right) = -1.20 \times 10^{-9} \text{ N} = \boxed{-1.20 \text{ nN}}$$

- P43.60** (a) For equilibrium, $\frac{dU}{dx} = 0$: $\frac{d}{dx}(Ax^{-3} - Bx^{-1}) = -3Ax^{-4} + Bx^{-2} = 0$

$x \rightarrow \infty$ describes one equilibrium position, but the stable equilibrium position is at

$$3Ax_0^{-2} = B \quad \text{or} \quad \boxed{x_0 = \sqrt{\frac{3A}{B}}}$$

- (b) The depth of the well is given by $U_0 = U|_{x=x_0} = \frac{A}{x_0^3} - \frac{B}{x_0} = \frac{AB^{3/2}}{3^{3/2}A^{3/2}} - \frac{BB^{1/2}}{3^{1/2}A^{1/2}} = \boxed{-2\sqrt{\frac{B^3}{27A}}}$.

- (c) $F_x = -\frac{dU}{dx} = 3Ax^{-4} - Bx^{-2}$

To find the maximum force, we determine finite x_m such that

$$\left.\frac{dF_x}{dx}\right|_{x=x_m} = \left[-12Ax^{-5} + 2Bx^{-3}\right]_{x=x_m} = 0 \text{ then } F_{\max} = 3A\left(\frac{B}{6A}\right)^2 - B\left(\frac{B}{6A}\right) = \boxed{-\frac{B^2}{12A}}$$

P43.61 (a) At equilibrium separation, $r = r_e$, $\left. \frac{dU}{dr} \right|_{r=r_e} = -2aB \left[e^{-a(r_e-r_0)} - 1 \right] e^{-a(r_e-r_0)} = 0$

We have neutral equilibrium as $r_e \rightarrow \infty$ and stable equilibrium at $e^{-a(r_e-r_0)} = 1$,

or $r_e = \boxed{r_0}$

(b) At $r = r_0$, $U = 0$. As $r \rightarrow \infty$, $U \rightarrow B$. The depth of the well is \boxed{B} .

(c) We expand the potential in a Taylor series about the equilibrium point:

$$U(r) \approx U(r_0) + \left. \frac{dU}{dr} \right|_{r=r_0} (r-r_0) + \frac{1}{2} \left. \frac{d^2U}{dr^2} \right|_{r=r_0} (r-r_0)^2$$

$$U(r) \approx 0 + 0 + \frac{1}{2}(-2Ba) \left[-ae^{-2(r-r_0)} - ae^{-(r-r_0)} (e^{-2(r-r_0)} - 1) \right]_{r=r_0} (r-r_0)^2 \approx Ba^2 (r-r_0)^2$$

This is of the form $\frac{1}{2} kx^2 = \frac{1}{2} k(r-r_0)^2$

for a simple harmonic oscillator with $k = 2Ba^2$

Then the molecule vibrates with frequency $f = \frac{1}{2\pi} \sqrt{\frac{k}{\mu}} = \frac{a}{2\pi} \sqrt{\frac{2B}{\mu}} = \boxed{\frac{a}{\pi} \sqrt{\frac{B}{2\mu}}}$

(d) The zero-point energy is $\frac{1}{2} \hbar \omega = \frac{1}{2} \hbar f = \frac{\hbar a}{\pi} \sqrt{\frac{B}{8\mu}}$

Therefore, to dissociate the molecule in its ground state requires energy $\boxed{B - \frac{\hbar a}{\pi} \sqrt{\frac{B}{8\mu}}}$.

P43.62

	$T = 0$		$T = 0.1T_F$		$T = 0.2T_F$		$T = 0.5T_F$	
$\frac{E}{E_F}$	$e^{[(E/E_F)-1](T_F/T)}$	$f(E)$	$e^{[(E/E_F)-1](T_F/T)}$	$f(E)$	$e^{[(E/E_F)-1](T_F/T)}$	$f(E)$	$e^{[(E/E_F)-1](T_F/T)}$	$f(E)$
0	$e^{-\infty}$	1.00	$e^{-10.0}$	1.000	$e^{-5.00}$	0.993	$e^{-2.00}$	0.881
0.500	$e^{-\infty}$	1.00	$e^{-5.00}$	0.993	$e^{-2.50}$	0.924	$e^{-1.00}$	0.731
0.600	$e^{-\infty}$	1.00	$e^{-4.00}$	0.982	$e^{-2.00}$	0.881	$e^{-0.800}$	0.690
0.700	$e^{-\infty}$	1.00	$e^{-3.00}$	0.953	$e^{-1.50}$	0.818	$e^{-0.600}$	0.646
0.800	$e^{-\infty}$	1.00	$e^{-2.00}$	0.881	$e^{-1.00}$	0.731	$e^{-0.400}$	0.599
0.900	$e^{-\infty}$	1.00	$e^{-1.00}$	0.731	$e^{-0.500}$	0.622	$e^{-0.200}$	0.550
1.00	e^0	0.500	e^0	0.500	e^0	0.500	e^0	0.500
1.10	$e^{+\infty}$	0.00	$e^{1.00}$	0.269	$e^{0.500}$	0.378	$e^{0.200}$	0.450
1.20	$e^{+\infty}$	0.00	$e^{2.00}$	0.119	$e^{1.00}$	0.269	$e^{0.400}$	0.401
1.30	$e^{+\infty}$	0.00	$e^{3.00}$	0.047 4	$e^{1.50}$	0.182	$e^{0.600}$	0.354
1.40	$e^{+\infty}$	0.00	$e^{4.00}$	0.018 0	$e^{2.00}$	0.119	$e^{0.800}$	0.310
1.50	$e^{+\infty}$	0.00	$e^{5.00}$	0.006 69	$e^{2.50}$	0.075 9	$e^{1.00}$	0.269

Fermi-Dirac Distribution Function

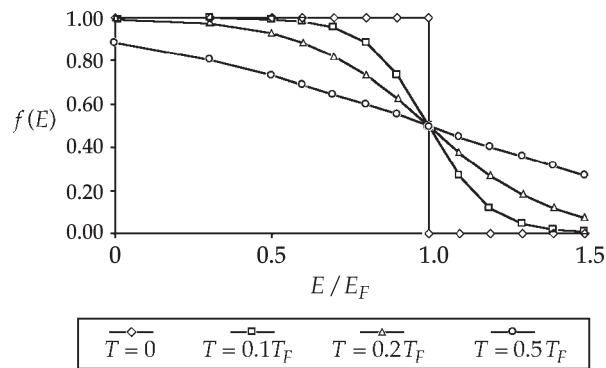


FIG. P43.62

ANSWERS TO EVEN PROBLEMS

P43.2 4.3 eV

P43.4 (a) 1.28 eV (b) $\sigma = 0.272$ nm, $\epsilon = 4.65$ eV (c) 6.55 nN (d) 576 N/mP43.6 (a) 0.0148 eV (b) 83.8 μm P43.8 12.2×10^{-27} kg; 12.4×10^{-27} kg; They agree, because the small apparent difference can be attributed to uncertainty in the data.

P43.10 $1.46 \times 10^{-46} \text{ kg} \cdot \text{m}^2$

P43.12 (a) $1.81 \times 10^{-45} \text{ kg} \cdot \text{m}^2$ (b) 1.62 cm

P43.14 (a) 12.1 pm (b) 9.23 pm (c) HI is more loosely bound since it has the smaller k value.

P43.16 (a) 0, 364 μeV , 1.09 meV (b) 98.2 meV, 295 meV, 491 meV

P43.18 (a) 472 μm (b) 473 μm (c) 0.715 μm

P43.20 (a) $4.60 \times 10^{-48} \text{ kg} \cdot \text{m}^2$ (b) $1.32 \times 10^{14} \text{ Hz}$ (c) 0.074 1 nm

P43.22 6.25×10^9

P43.24 (a) $\sim 10^{17}$ (b) $\sim 10^5 \text{ m}^3$

P43.26 (a) 0.444 nm, 0.628 nm, 0.769 nm

P43.28 (a) The Fermi energy is proportional to the spatial concentration of free electrons to the two-thirds power. (c) 6.06; copper by 3.33 times; it agrees with the equation because $6.06^{2/3} = 3.33$.

P43.30 0.938

P43.32 (a) $2.54 \times 10^{28} \text{ electron/m}^3$ (b) 3.15 eV

P43.34 2%

P43.36 $3.40 \times 10^{17} \text{ electrons}$

P43.38 See the solution.

P43.40 All of the Balmer lines are absorbed, except for the red line at 656 nm, which is transmitted.

P43.42 1.91 eV

P43.44 -0.0219 eV , 2.81 nm

P43.46 4.4 V

P43.48 (a) At $\Delta V = 0.200 \text{ V}$, $I_D = I_w = 2.98 \text{ mA}$, agreeing to three digits. (b) 67.1Ω (c) 8.39Ω

P43.50 (a) In the definition of resistance $\Delta V = IR$, if R is zero then $\Delta V = 0$ for any value of current. (b) The graph shows direct proportionality with resistance 0.0232Ω . (c) Expulsion of magnetic flux and therefore fewer current-carrying paths could explain the decrease in current.

P43.52 37

P43.54 5.23 J/g

P43.56 4.74 eV

P43.58 (c) 9.18 THz

P43.60 (a) $x_0 = \sqrt{\frac{3A}{B}}$ (b) $-2\sqrt{\frac{B^3}{27A}}$ (c) $-\frac{B^2}{12A}$

P43.62 See the solution.