

## Week 7

# Molecular Spectroscopy and Group Theory

## 7.1 Hydrogen Molecule

- 11/8: • Reviews what would happen if electrons were bosons.

– The wave function  $\psi$  of the lithium atom would be

$$\psi(123) = 1s\alpha(1) \vee 1s\alpha(2) \vee 1s\alpha(3)$$

– Reviews wedge products.

– Conclusion: All electrons could occupy the same orbital.

- A sodium atom (the nucleus and the electrons jointly) acts like a boson.

– At temperatures on the order of microkelvin,  $10^{11}$  atoms have been placed in the same ground-state orbital.

– These substances are known as **Bose-Einstein condensates**.

– We use a magnetic field to confine the atoms to a harmonic potential. Since the atoms form a Gaussian curve at the bottom of said potential, they are all in the ground state (see Figure 3.3).

– Evaporative cooling and laser cooling allow you to reach such temperatures.

– Fermionic atoms cannot condense in such a way (because of the Pauli Exclusion Principle).

– Superconductivity is a condensation phenomena.

– Bose-Einstein condensates were predicted by Einstein in the 1930s but not experimentally verified until the 1990s.

– A very dilute gas was used here. In such a condition, the atoms feel the statistics force of the wedge product which forces them into such a state.

- Consider the Boron atom:

– It has 5 electrons.

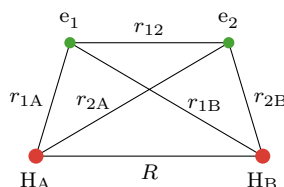
– It's electron configuration is  $1s^2 2s^2 sp^1$ .

– It's wave function is

$$\psi(12345) = 1s\alpha(1) \wedge 1s\beta(2) \wedge 2s\alpha(3) \wedge 2s\beta(4) \wedge 2p\alpha(5)$$

- Recall that this is not the exact wave function; this is still a product of hydrogenlike orbitals at the Hartree-Fock level.

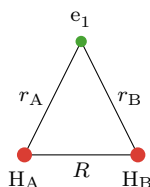
- More general wave functions can be used to obtain more accurate results.
- Consider the diatomic molecule  $\text{H}_2$ .

Figure 7.1:  $\text{H}_2$  distances.

- We have hydrogen atoms  $\text{H}_\text{A}$  and  $\text{H}_\text{B}$ , separated by a distance  $R$ .
- We have electrons  $\text{e}_1$  and  $\text{e}_2$ .
- The distance from object  $i$  to  $j$  where  $i, j = \text{A}, \text{B}, 1, 2$  and  $i \neq j$  is  $r_{ij}$ .
- Hamiltonian:

$$\hat{H} = -\frac{1}{2}(\nabla_1^2 + \nabla_2^2) - \frac{1}{r_{1\text{A}}} - \frac{1}{r_{1\text{B}}} - \frac{1}{r_{2\text{A}}} - \frac{1}{r_{2\text{B}}} + \frac{1}{r_{12}} + \frac{1}{R}$$

- This is pretty complicated.
- Thus, let's start with the hydrogen molecular ion ( $\text{H}_2^+$ ).

Figure 7.2:  $\text{H}_2^+$  distances.

- Hamiltonian:

$$\hat{H} = -\frac{1}{2}\nabla^2 - \frac{1}{r_\text{A}} - \frac{1}{r_\text{B}} + \frac{1}{R}$$

- This *can* be solved exactly in cylindrical coordinates, but it's nasty.
- Thus, let's approximate with the following variational wave function (originally by Heitler and London in the 1960s).

$$\psi(1) = c_1 1s_\text{A} + c_2 1s_\text{B}$$

- Albeit simple, this wave function gives pretty good results.
- By the variational principle,  $\mathbb{H}\vec{c} = E\mathbb{S}\vec{c}$ , or

$$\begin{vmatrix} H_{\text{AA}} - ES_{\text{AA}} & H_{\text{AB}} - ES_{\text{AB}} \\ H_{\text{BA}} - ES_{\text{BA}} & H_{\text{BB}} - ES_{\text{BB}} \end{vmatrix} = 0$$

solves for  $E$ .

– We have that

$$\begin{aligned}H_{AA} &= H_{BB} = \int d\vec{r} 1s_A^* \hat{H} 1s_A = \int d\vec{r} 1s_B^* \hat{H} 1s_B \\H_{AB} &= H_{BA} = \int d\vec{r} 1s_A^* \hat{H} 1s_B = \int d\vec{r} 1s_B^* \hat{H} 1s_A \\S_{AA} &= S_{BB} = \int d\vec{r} 1s_A^* 1s_A = \int d\vec{r} 1s_B^* 1s_B \\S_{AB} &= S_{BA} = \int d\vec{r} 1s_A^* 1s_B = \int d\vec{r} 1s_B^* 1s_A\end{aligned}$$

– We can show that

$$\begin{aligned}H_{AA} &= H_{BB} = E_{1s} + J \\H_{AB} &= H_{BA} = E_{1s}S + K\end{aligned}$$

where  $E_{1s}$  is the energy of the  $1s$  orbital of the hydrogen atom,  $J$  is the **Coulomb integral**

$$J = \int d\vec{r} 1s_A^* \left( -\frac{1}{r_B} + \frac{1}{R} \right) 1s_A$$

and  $K$  is the **exchange integral**

$$K = \int d\vec{r} 1s_B^* \left( -\frac{1}{r_B} + \frac{1}{R} \right) 1s_A$$

## 7.2 The Hydrogen Molecular Ion

11/10: • Continuing from last time, the determinant for the equation  $\mathbb{H}\vec{c}_n = E_n\mathbb{S}\vec{c}_n$  is

$$\begin{vmatrix} E_{1s} + J - E & E_{1s}S + K \\ E_{1s}S + K & E_{1s} + J - E \end{vmatrix}$$

- Therefore, the characteristic polynomial is a quadratic equation in  $E$ .
- Solving said quadratic gives us

$$E_{\pm} = E_{1s} + \frac{J \pm K}{1 \pm S}$$

where

$$J(R) = e^{-2R} \left( 1 + \frac{1}{R} \right) \quad S(R) = e^{-R} \left( 1 + R + \frac{R^2}{3} \right) \quad K(R) = \frac{S(R)}{R} - e^{-R}(1 + R)$$

- We then determine  $\vec{c}_n$  in the two different cases. But this yields

$$|c_1| = |c_2| = k$$

- Therefore,

$$\psi_{\pm} = k(1s_A \pm 1s_B)$$

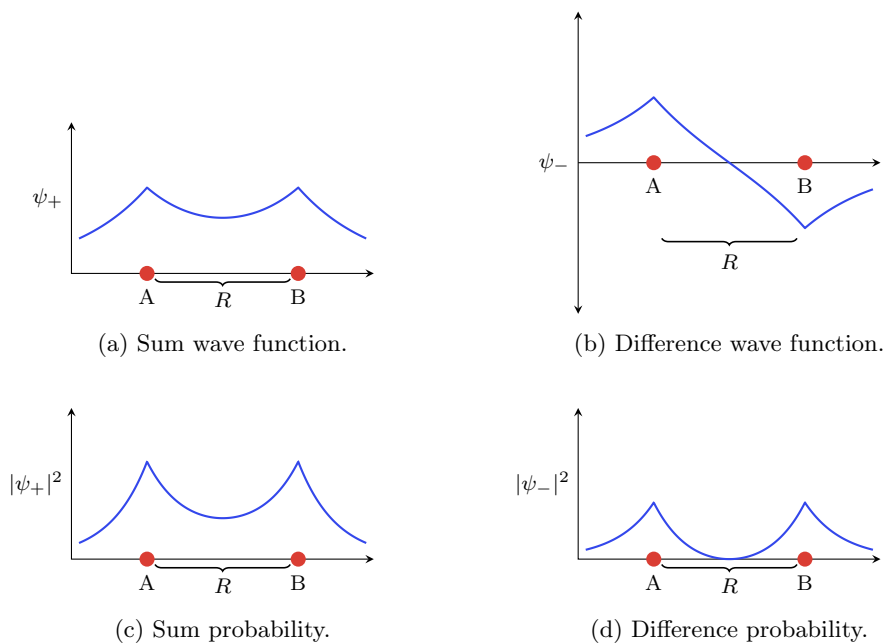


Figure 7.3: Hydrogen ion bonding.

- Note that in  $\psi_-$ , a node arises naturally from the quantum mechanics.
- Thus,  $\psi_+$  is a bonding orbital and  $\psi_-$  is an antibonding orbital.
- We now consider the **potential energy surface** or **PES** of the molecule.

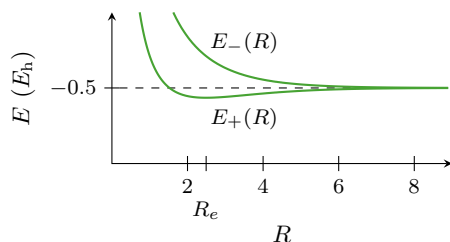


Figure 7.4: Potential energy surface of the hydrogen molecular ion.

- The  $x, y$ -axis units are Bohrs and Hartrees, respectively.
- The bound state only occurs in the bonding orbital; if the electron is excited to the antibonding orbital, the atoms will drift apart to  $\infty$  to minimize energy.
- **Born-Oppenheimer approximation.**
  - Throughout this derivation, we neglected the kinetic energy of the nuclei.
  - Thus, technically the total Hamiltonian is

$$\hat{H}_{\text{tot}} = -\frac{\hbar^2}{2M}(\hat{\nabla}_A^2 + \hat{\nabla}_B^2) + \hat{H}_{\text{electr}}$$

where  $\hat{H}_{\text{electr}}$  is the Hamiltonian associated with Figure 7.2.

- We have assumed that the nuclei are fixed relative to the motion of the electrons. We can do this because  $m_e/M \approx 10^{-3}$ , i.e., the electrons travel much faster than the nuclei. Therefore, the kinetic energy of the electrons is more important.

- The wave functions of the nuclei (which do exist) are very sharp peaks, so the nuclei don't move much, so we may regard them as fixed.
- **Molecular orbital:** A linear combination of atomic orbitals. *Also known as MO.*
- Example ( $H_2$ ):
  - $\psi_{\pm} = 1s_A \pm 1s_B$  (bonding and antibonding).
  - $\phi_{MO} = \phi_{1s_A} + \phi_{1s_B}$ .
  - $\phi(12) = \phi_{MO}\alpha(1)\wedge\phi_{MO}\beta(2)$ ; thus, the MO diagram is connected back to the rigorous mathematics of Schrödinger.
- Filling rules: Fill the MOs that are lower in energy first.
- Example ( $C_2$ ):
  - The MO diagram is identical to Figure III.17 from Labalme (2021) except that the  $\sigma_g$  corresponding to the  $2p$  orbitals has higher energy than the  $\pi_u$ 's due to mixing.

## 7.3 Huckel Theory

11/12: • Reviews that diatomics with more electrons will have less mixing.

- **Bond order:** A measure of stability. *Given by*

$$BO = \frac{1}{2}[(\# \text{ of electrons in } BO_1) - (\# \text{ of electrons in } ABO_1)]$$

- For example, for  $C_2$ , we will have  $BO = \frac{1}{2}(8 - 4) = 2$ .
- Huckel was a physicist/chemist from the 1930s who worked out the MO theory for conjugated molecules.
- Huckel's strategy.
  1.  $\mathbb{H}\vec{c} = E\vec{S}\vec{c}$  becomes  $\mathbb{H}\vec{c} = E\vec{c}$ , where the only orbitals considered are the  $p_z$  orbitals.
  2. We let  $\mathbb{S} = \mathbb{I}$ , i.e., we assume all orbitals are orthonormal.  $S_{ij} = \delta_{ij}$ .
  3.  $H_{ii} = \alpha$  (the energy of the electrons in  $p_z$ ).
    - $H_{i,i+1} = H_{i+1,i} = \beta$  (interaction between adjacent  $p_z$  orbitals).
    - Everything else is zero!
- Example: Ethene.

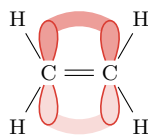


Figure 7.5: Ethene orbital diagram.

- The Hamiltonian matrix is

$$\mathbb{H} = \begin{pmatrix} \alpha & \beta \\ \beta & \alpha \end{pmatrix}$$

- If we let  $(\alpha - E)/\beta = x$ , then

$$\begin{aligned} 0 &= \begin{vmatrix} \alpha - E & \beta \\ \beta & \alpha - E \end{vmatrix} \\ &= \frac{1}{\beta^2} \begin{vmatrix} \alpha - E & \beta \\ \beta & \alpha - E \end{vmatrix} \\ &= \begin{vmatrix} x & 1 \\ 1 & x \end{vmatrix} \end{aligned}$$

- Thus, our characteristic polynomial is

$$\begin{aligned} 0 &= x^2 - 1 \\ &= (x + 1)(x - 1) \end{aligned}$$

so  $x = \pm 1$ .

- It follows from returning the substitution that  $\alpha \pm \beta = E_{\mp}$ .
- This yields the following energy diagram.

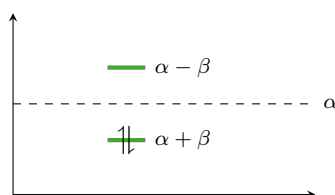


Figure 7.6: Ethene energy diagram.

- Note that the ground state MO is more stable than the 1-electron in each  $p_z$  orbital scenario; thus bonding occurs.
- It follows that

$$\psi_{\alpha+\beta} = 2p_{zA} + 2p_{zB} \qquad \psi_{\alpha-\beta} = 2p_{zA} - 2p_{zB}$$

■ Thus,  $\psi_{\alpha+\beta}$  has  $\pi_u$  symmetry and  $\psi_{\alpha-\beta}$  has  $\pi_g$  symmetry.

- Example: 1,3-butadiene.

- Our determinant here will be

$$\begin{aligned} 0 &= \begin{vmatrix} \alpha - E & \beta & 0 & 0 \\ \beta & \alpha - E & \beta & 0 \\ 0 & \beta & \alpha - E & \beta \\ 0 & 0 & \beta & \alpha - E \end{vmatrix} \\ &= \begin{vmatrix} x & 1 & 0 & 0 \\ 1 & x & 1 & 0 \\ 0 & 1 & x & 1 \\ 0 & 0 & 1 & x \end{vmatrix} \\ &= x^4 - 3x^2 + 1 \\ &= y^2 - 3y + 1 \\ y &= \frac{3 \pm \sqrt{5}}{2} \\ x &= \pm 1.618, \pm 0.618 \end{aligned}$$

- Thus, our energy diagram will be

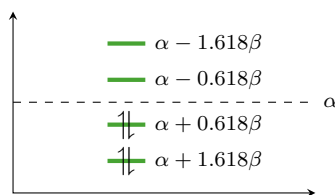


Figure 7.7: 1,3-butadiene energy diagram.

- This yields the bond order  $BO = \frac{1}{2}(4 - 0) = 2$ .
- Solving for the possible  $\vec{c}$ 's yields four wave function LCAOs analogous to the particle in a box wave functions (even function, odd function with one node, even function with two nodes, odd function with three nodes).
  - Thus, the Huckel approximation agrees with the approximation of four particles in a box.
- Example 3: 1,3,5-hexatriene.
  - Working out the determinant yields

$$\begin{aligned} 0 &= x^6 - 5x^4 + 6x^2 - 1 \\ &= y^3 - 5y^2 + 6y - 1 \end{aligned}$$

- Our energy diagram is as one might expect with 3 bonding orbitals and 3 antibonding orbitals.

## 7.4 Office Hours (Mazziotti)

- How does the asymptotic analysis guarantee us the  $n = 1$  solution, from Problem Set 5.1e?
  - $n = 1$  dominates in the asymptotic analysis, especially among the ground states.
- Math that we're using?
  - We're doing a lot of linear algebra, ordinary differential equations, and partial differential equations (boundary condition differential equations). Typically elliptic boundary conditions.
  - Eigenvalue equations, determinants, etc.
  - We're in a Hilbert space. Hilbert spaces are subsets of the Banach spaces, so all of that linear algebra applies.
  - Differential equations in a subspace can be rewritten as eigenvalue equations?
  - Ties into real analysis and complex analysis with  $e^{i\phi}$ .
  - The Grassmann algebra is a piece of classical mathematics that plays in.
  - Point groups and spin groups fall under abstract algebra; more specifically, Lie algebra.

## 7.5 Chapter 9: The Chemical Bond — Diatomic Molecules

From McQuarrie and Simon (1997).

- 11/8:
- Quantum mechanics was the first theory to explain why atoms combined to form a stable bond.
  - Since  $\text{H}_2^+$  has the simplest chemical bond, we will discuss it in detail.
    - The ideas developed will be applicable to more complex molecules, motivating molecular orbitals.
  - Describes the Hamiltonian for  $\text{H}_2$ , as in the discussion associated with Figure 7.1.

- **Born-Oppenheimer approximation:** The approximation of neglecting the nuclear motion, allowing us to ignore  $\nabla_{A,B}$  terms.
  - We can correct for the BO approximation using perturbation theory, but realistically we don't really need to (corrections are on the order of the mass ratio  $10^{-3}$ ).
- **Molecular-orbital theory:** The method we will use to describe the bonding properties of molecules.
- **Molecular orbital:** A single-electron wave function corresponding to a molecule.
- Like we constructed atomic wave functions in terms of determinants involving atomic orbitals, we will construct molecular wave functions in terms of determinants involving molecular orbitals.
- Note that  $\text{H}_2^+$  is a stable, well-studied species in real life.
- Although the Schrödinger equation for  $\text{H}_2^+$  can be solved exactly within the BO approximation, the solutions are not easy to use and their mathematical form gives little physical insight into how and why bonding occurs.
  - Thus, we use approximate solutions that provide good physical insight and are in good agreement with experimental observations.
- As a first trial wave function  $\psi(r_A, r_B; R)$ , use

$$\psi_{\pm} = c_1 1s_A \pm c_2 1s_B$$

where  $1s_{A,B}$  are the hydrogen atomic orbitals centered on nuclei A and B, respectively.

- By symmetry,  $c_1 = c_2$  for  $\text{H}_2^+$ .
- **LCAO molecular orbital:** A molecular orbital that is a linear combination of atomic orbitals.
- We seek to find  $E_{\pm}$  by taking the quotient the integrals  $\int d\mathbf{r} \psi_{\pm}^* \hat{H} \psi_{\pm}$  and  $\int d\mathbf{r} \psi_{\pm}^* \psi_{\pm}$ .
- Considering  $\int d\mathbf{r} \psi_{\pm}^* \psi_{\pm}$  first, we are lead to define the **overlap integral**.
- **Overlap integral:** The following integral, which is only significant where there is a large overlap between the two hydrogenlike atomic orbitals. *Denoted by  $S$ . Given by*

$$S = \int d\mathbf{r} n l_A^* n l_B = \int d\mathbf{r} n l_B^* n l_A = \int d\mathbf{r} n l_A n l_B$$



Figure 7.8: Overlap integral vs. internuclear distance.

- As  $R \rightarrow 0$ ,  $S \rightarrow 1$ . As  $R \rightarrow \infty$ ,  $S \rightarrow 0$ .
- The overlap integral when  $nl = 1s$  can be evaluated analytically, giving

$$S(R) = e^{-R} \left( 1 + R + \frac{R^2}{3} \right)$$



- The overlap integral allows us to express  $\int d\mathbf{r} \psi_{\pm}^* \psi_{\pm}$  in the following convenient form.

$$\begin{aligned} \int d\mathbf{r} \psi_{+}^* \psi_{+} &= \int d\mathbf{r} (1s_A^* + 1s_B^*)(1s_A + 1s_B) \\ &= \int d\mathbf{r} 1s_A^* 1s_A + \int d\mathbf{r} 1s_A^* 1s_B + \int d\mathbf{r} 1s_B^* 1s_A + \int d\mathbf{r} 1s_B^* 1s_B \\ &= 1 + S + S + 1 \\ &= 2(1 + S) \end{aligned}$$

- It follows that the normalized  $\psi_{\pm}$  are

$$\psi_{\pm} = \frac{1}{\sqrt{2(1 \pm S)}} (1s_A \pm 1s_B)$$

11/14:

- We now look to evaluate the integral  $\int d\mathbf{r} \psi_{+}^* \hat{H} \psi_{+}$ .
- To begin, we have that

$$\begin{aligned} \int d\mathbf{r} \psi_{+}^* \hat{H} \psi_{+} &= \int d\mathbf{r} (1s_A^* + 1s_B^*) \left( -\frac{1}{2} \nabla^2 - \frac{1}{r_A} - \frac{1}{r_B} + \frac{1}{R} \right) (1s_A + 1s_B) \\ &= \int d\mathbf{r} (1s_A^* + 1s_B^*) \left( -\frac{1}{2} \nabla^2 - \frac{1}{r_A} - \frac{1}{r_B} + \frac{1}{R} \right) 1s_A \\ &\quad + \int d\mathbf{r} (1s_A^* + 1s_B^*) \left( -\frac{1}{2} \nabla^2 - \frac{1}{r_A} - \frac{1}{r_B} + \frac{1}{R} \right) 1s_B \\ &= \int d\mathbf{r} (1s_A^* + 1s_B^*) \left( E_{1s} - \frac{1}{r_B} + \frac{1}{R} \right) 1s_A \\ &\quad + \int d\mathbf{r} (1s_A^* + 1s_B^*) \left( E_{1s} - \frac{1}{r_A} + \frac{1}{R} \right) 1s_B \\ &= \int d\mathbf{r} \left( E_{1s} - \frac{1}{r_B} + \frac{1}{R} \right) 1s_A^* 1s_A + \int d\mathbf{r} \left( E_{1s} - \frac{1}{r_B} + \frac{1}{R} \right) 1s_B^* 1s_A \\ &\quad + \int d\mathbf{r} \left( E_{1s} - \frac{1}{r_B} + \frac{1}{R} \right) 1s_A^* 1s_B + \int d\mathbf{r} \left( E_{1s} - \frac{1}{r_B} + \frac{1}{R} \right) 1s_B^* 1s_B \\ &= E_{1s} \cdot 1 + \int d\mathbf{r} \left( -\frac{1}{r_B} + \frac{1}{R} \right) 1s_A^* 1s_A + E_{1s} \cdot S + \int d\mathbf{r} \left( -\frac{1}{r_B} + \frac{1}{R} \right) 1s_B^* 1s_A \\ &\quad + E_{1s} \cdot 1 + \int d\mathbf{r} \left( -\frac{1}{r_B} + \frac{1}{R} \right) 1s_A^* 1s_B + E_{1s} \cdot S + \int d\mathbf{r} \left( -\frac{1}{r_B} + \frac{1}{R} \right) 1s_B^* 1s_B \\ &= 2E_{1s}(1 + S) \\ &\quad + \int d\mathbf{r} \left( -\frac{1}{r_B} + \frac{1}{R} \right) 1s_A^* 1s_A + \int d\mathbf{r} \left( -\frac{1}{r_B} + \frac{1}{R} \right) 1s_B^* 1s_A \\ &\quad + \int d\mathbf{r} \left( -\frac{1}{r_B} + \frac{1}{R} \right) 1s_A^* 1s_B + \int d\mathbf{r} \left( -\frac{1}{r_B} + \frac{1}{R} \right) 1s_B^* 1s_B \end{aligned}$$

where  $E_{1s} = -E_h/2$  is the ground-state energy of the hydrogen atom (the energy corresponding to the  $1s_A$  wave function).

- **Coulomb integral:** The following integral, which reflects both the charge density of the electron about nucleus A interacting with nucleus B via the Coulomb potential and the internuclear repulsion. Denoted by  $J$ . Given by

$$J = \int d\mathbf{r} 1s_A^* \left( -\frac{1}{r_B} + \frac{1}{R} \right) 1s_A$$

- **Exchange integral:** The following integral. Denoted by  $K$ . Given by

$$K = \int d\mathbf{r} \, 1s_B^* \left( -\frac{1}{r_B} + \frac{1}{R} \right) 1s_A$$

- The exchange integral describes a purely quantum-mechanical effect; it has no analogy in classical mechanics.

- Using the definitions of the Coulomb and exchange integrals, we have that

$$\int d\mathbf{r} \, \psi_+^* \hat{H} \psi_+ = 2E_{1s}(1 + S) + 2J + 2K$$

- We can now determine a final expression for the energy  $E_+$  corresponding to  $\psi_+$ .

$$\begin{aligned} E_+ &= \frac{\int d\mathbf{r} \, \psi_+^* \hat{H} \psi_+}{\int d\mathbf{r} \, \psi_+^* \psi_+} \\ &= \frac{2E_{1s}(1 + S) + 2J + 2K}{2(1 + S)} \\ &= E_{1s} + \frac{J + K}{1 + S} \end{aligned}$$

- The Coulomb and exchange integrals can be evaluated analytically, giving

$$J = e^{-2R} \left( 1 + \frac{1}{R} \right) \qquad K = \frac{S}{R} - e^{-R}(1 + R)$$

- Note that since the Coulomb integral is always positive, the exchange integral is entirely responsible for the existence of the chemical bond in  $H_2^+$ .
- This highlights the importance of the quantum-mechanical nature of the chemical bond.

- **Bonding orbital:** A state that exhibits a stable chemical bond.

- Example:  $\psi_+$ .

- **Antibonding orbital:** A state that leads to a repulsive interaction between the two nuclei for all internuclear distances.

- Example:  $\psi_-$ .

- The bonding orbital  $\psi_b = \psi_+$  describes the ground state of  $H_2^+$ , while the antibonding orbital  $\psi_a = \psi_-$  describes an excited state.
- Note that we have only found two molecular orbitals (as opposed to the infinitely many hydrogenlike atomic orbitals) because we used a trial wave function that was the linear combination of only two atomic orbitals. We could use longer linear combinations to find more molecular orbitals, but for pedagogical reasons, we will limit ourselves to two for now.
- “Because  $\psi_b$  is the molecular orbital corresponding to the ground-state energy of  $H_2^+$ , we can describe the ground state of  $H_2$  by placing two electrons with opposite spins in  $\psi_b$ , just as we placed two electrons in a  $1s$  atomic orbital to describe the helium atom” (McQuarrie & Simon, 1997, p. 336).
- This leads to the Slater determinantal wave function

$$\psi = \frac{1}{\sqrt{2!}} \begin{vmatrix} \psi_b\alpha(1) & \psi_b\beta(1) \\ \psi_b\alpha(2) & \psi_b\beta(2) \end{vmatrix}$$

for  $H_2$ .

- As before, the spatial and spin parts of this two-electron wave function separate.
- It follows that the spatial molecular wave function is

$$\begin{aligned}\psi_{\text{MO}} &= \psi_{\text{b}}(1)\psi_{\text{b}}(2) \\ &= \frac{1}{2(1+S)}[1s_{\text{A}}(1) + 1s_{\text{B}}(1)][1s_{\text{A}}(2) + 1s_{\text{B}}(2)]\end{aligned}$$

- **Linear combination of atomic orbitals-molecular orbitals method:** The method of constructing molecular wave functions by taking the product of molecular orbitals, which are in turn linear combinations of atomic orbitals. *Also known as LCAO-MO method.*

- This is how we constructed  $\psi_{\text{MO}}$ , above.
- Knowing that  $\psi_{\text{MO}}$  is normalized, we have that

$$E_{\text{MO}} = \int d\mathbf{r}_1 d\mathbf{r}_2 \psi_{\text{MO}}^*(1,2) \hat{H} \psi_{\text{MO}}(1,2)$$

- **$\sigma$  orbital:** An orbital that is symmetric about the internuclear axis.
  - Both  $\psi_{\pm}$  are  $\sigma$  orbitals.
  - Molecular orbitals constructed from  $1s$  orbitals are denoted by  $\sigma 1s$ .
- Distinguishing between  $\sigma 1s$  bonding and antibonding orbitals.
  - We may let  $\sigma 1s$  refer to  $\psi_+$  and  $\sigma^* 1s$  refer to  $\psi_-$ .
  - We may let  $\sigma_g 1s$  refer to  $\psi_+$  ( $g$  being short for “gerade” [the German word for even] since  $\psi_+$  does not change sign under inversion) and  $\sigma_u 1s$  refer to  $\psi_-$  ( $u$  being short for “ungerade” [the German word for odd] since  $\psi_-$  does change sign under inversion).
  - McQuarrie and Simon (1997) will favor the latter notation.
- $\sigma 2s$  molecular orbitals.
  - Of the form  $2s_{\text{A}} \pm 2s_{\text{B}}$ .
  - Have radial nodes about each nuclei (owing to the structure of the  $2s$  hydrogenlike atomic orbital) in addition to the possible planar node in the middle of the molecule.
  - Have higher energies than  $\sigma 1s$  MOs since they’re associated with higher energy atomic orbitals. This can be demonstrated rigorously the same way we calculated the energies for the  $\sigma 1s$  MOs.
  - In terms of energy,  $\sigma_g 1s < \sigma_u 1s < \sigma_g 2s < \sigma_u 2s$ .
- $2p$  molecular orbitals.
  - Choose the internuclear axis to be the  $z$ -axis.
  - $2p_{z_{\text{A}}} \pm 2p_{z_{\text{B}}}$  are cylindrically symmetric about the internuclear axis and are therefore  $\sigma_u 2p_z$  and  $\sigma_g 2p_z$  orbitals, respectively.
  - $2p_{x,y_{\text{A}}} \pm 2p_{x,y_{\text{B}}}$  are  **$\pi$  orbitals**, denoted  $\pi_u 2p_{x,y}$  and  $\pi_g 2p_{x,y}$ , respectively.
  - $\pi_u 2p_x, \pi_u 2p_y$  and  $\pi_g 2p_x, \pi_g 2p_y$  are degenerate pairs of orbitals since they are identical except for their spatial orientation.
- **$\pi$  orbital:** A molecular orbital with one nodal plane that contains the internuclear axis.
- From  $\text{Li}_2$  through  $\text{N}_2$ , the energy order is

$$\sigma_g 2s < \sigma_u 2s < \pi_u 2p_{x,y} < \sigma_g 2p_z < \pi_g 2p_{x,y} < \sigma_u 2p_z$$

- From  $O_2$  through  $F_2$ , the energy order is

$$\sigma_g 2s < \sigma_u 2s < \sigma_g 2p_z < \pi_u 2p_{x,y} < \pi_g 2p_{x,y} < \sigma_u 2p_z$$

- Diatomic helium does not exist since the bonding and antibonding electrons cancel each other out, leaving only repulsive nuclei.
  - Bond order formalizes this notion.
  - Note that in 1993, Gentry and co. reported spectroscopic observations of  $He_2$  in a gas-phase sample of helium of temperature 0.001 K, possessing by far the weakest chemical bond known.
- Note that since there is little difference between the electron densities of core electron-derived molecular orbitals, we need only consider electrons in the valence shell when discussing chemical bonding.
- We denote the filled  $n = 1$  shell by  $K$ , e.g., the ground state electron configuration of  $Li_2$  is  $KK(\sigma_g 2s)^2$ .
- MO theory accurately predicts that  $O_2$  is paramagnetic.
  - MO theory also predicts bond orders of 2.5, 2, 1.5, 1 for  $O_2^+$ ,  $O_2$ ,  $O_2^-$ ,  $O_2^{2-}$ , respectively. This would suggest that bond length increases and bond energy decreases down this list, as we do indeed observe experimentally.
- McQuarrie and Simon (1997) provides data on the ground-state electron configuration, bond order, bond length, and bond energy for the homonuclear diatomics of lithium through neon.
- **Ionization energy:** The energy required to eject an electron from a molecule.
- **Photoelectron spectroscopy:** The measurement of the energies of the electrons ejected by radiation incident on gaseous molecules.
  - Goes through how PES supports MO theory, as on Labalme (2021, p. 56).
- **Heteronuclear diatomic molecule:** A diatomic molecule in which the two nuclei are different.
- For heteronuclear diatomics whose constituent atoms' atomic numbers differ by 1 or 2, the scheme we used for homonuclear diatomics is good enough.
- For heteronuclear diatomics whose constituent atoms' atomic numbers differ greatly (e.g., HF), we need a new scheme.
  - Noting that the energy of the  $1s$  atomic orbital of H is similar to the energy of the  $2p$  atomic orbitals of F, we look for constructive and destructive interference and find that  $1s_H$  and  $2p_{z_F}$  interact nicely.
  - Thus, a first approximation the molecular orbital would be  $\psi = c_1 1s_H + c_2 2p_{z_F}$ .
  - Note that both MOs have  $\sigma$  symmetry.
- The scheme presented thus far is the simplest possible.
- More generally, we may create trial wave functions that include more and orbitals, minimizing the coefficients with the variational method along the way, until we reach the Hartree-Fock limit.
- **SCF-LCAO-MO wave function:** A wave function obtained from molecular orbitals that are linear combinations of atomic orbitals whose coefficients are determined by a self-consistent field method.
  - Such orbitals, obtained from many atomic orbitals, cannot be meaningfully classified as  $\sigma 2s$  or  $\pi 2p$ , for example, so we classify them as the first  $\sigma_g$  orbital ( $1\sigma_g$ ), the first  $\sigma_u$  orbital ( $1\sigma_u$ ), and so on and so forth.
  - An SCF-LCAO-MO is only the same as a Hartree-Fock orbital if the SCF-LCAO-MO contains enough terms to reach the Hartree-Fock limit.

- **Hartree-Fock-Roothaan method:** The method for determining a SCF-LCAO-MO wave function.
- McQuarrie and Simon (1997) lists data on the Hartree-Fock limit vs. experimental calculations.
- Molecular term symbols.
- Excited states of molecules.
  - Consider  $\text{H}_2$  with one electron in the  $\sigma_g 1s$  orbital and one electron in the  $\sigma_g 2s$  orbital. This species has a slightly longer bond length than ground state  $\text{H}_2$ .