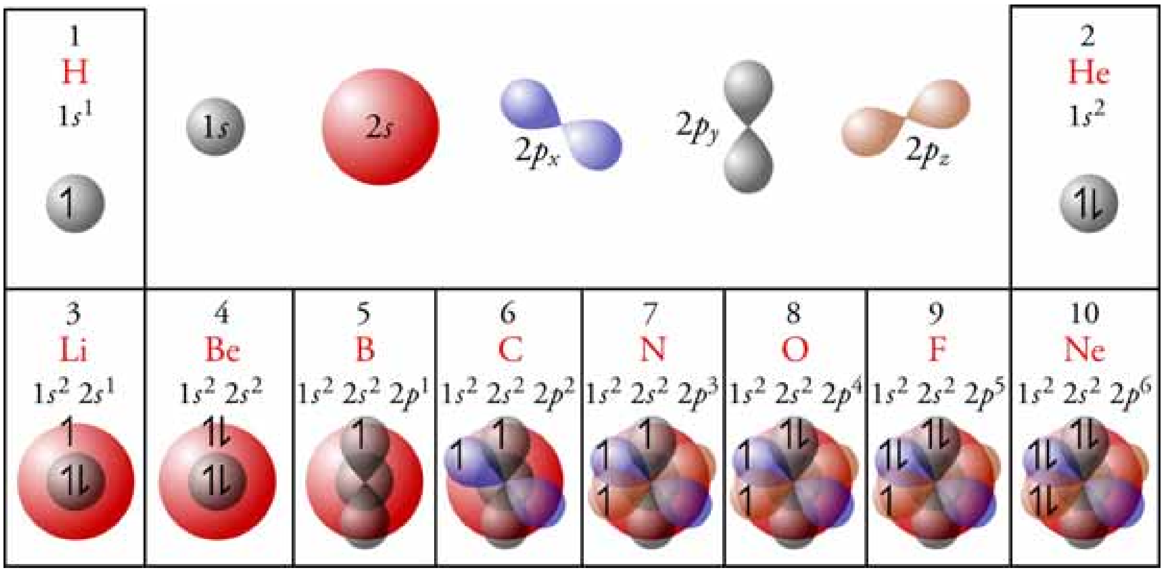
Chapter 11
Modern Atomic Theory



Section Goals and Introductions

Section 11.1 The Mysterious Electron

Goals

- *To explain why it is very difficult to describe the modern view of the electron.*
- *To give you some understanding of the nature of the electron by describing how it is like a guitar string.*
- *To explain what atomic orbitals are.*
- *To describe the atomic orbitals available to the electron of a hydrogen atom.*
- *To explain what energy levels and sublevels are.*

The electron is extremely tiny, and modern physics tells us that strange things happen in the realm of the very, very small. This makes it difficult for us to get a good understanding of the nature of the extremely tiny electron. For us, it's easier to consider what the electron is *like* rather than what it *is*. This section begins by giving you a glimpse of the modern view of the electron by showing how it is like a guitar string and how atomic orbitals that are possible for an electron in a hydrogen atom are like the possible ways that a guitar string can vibrate.

The most important component of this section is the introduction of the idea of atomic orbitals. Be sure you understand what the electron clouds that we call orbitals represent, both in terms of the effect they have on the space around the nucleus (which relates to their negative charge) and in terms of the probability of finding the electron in any position outside the nucleus. It will be useful for you to know the different shapes and sizes of the possible orbitals for the one electron in a hydrogen atom and to know how these orbitals can be arranged into energy levels and sublevels.

Section 11.2 Multi-Electron Atoms

Goals

- *To show how the knowledge of the atomic orbitals of hydrogen can be applied to atoms of the other elements.*
- *To describe how electrons of atoms are arranged with respect to orbitals, sublevels, and energy levels.*

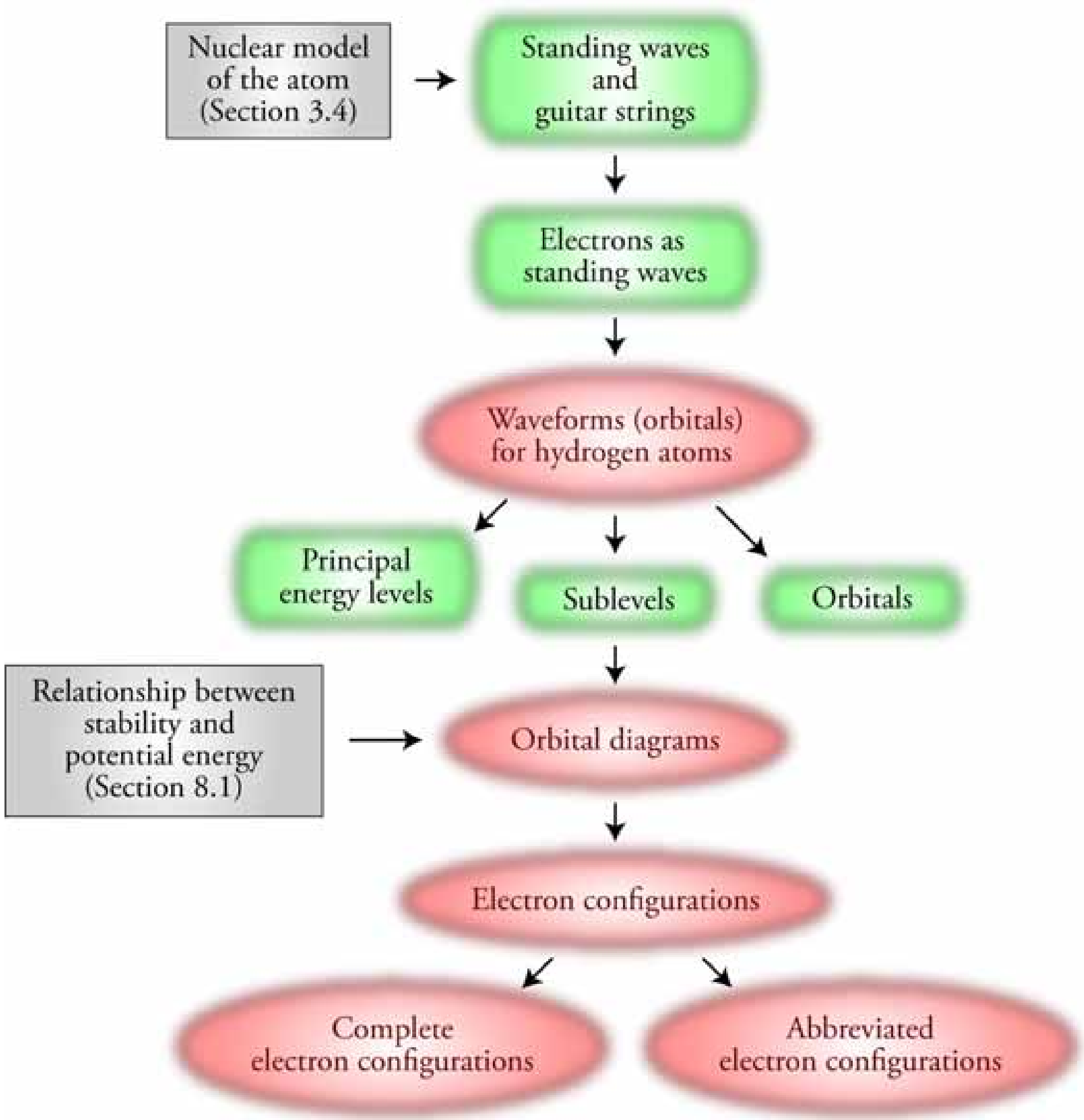
This section shows you how the information about the energy levels, sublevels, and orbitals for the hydrogen electron can be applied to the electrons in atoms of other elements. It's important that you learn how to describe the arrangement of electrons in these energy levels, sublevels, and orbitals with orbital diagrams and electron configurations. You will see in Chapter 12 that these orbital diagrams and electron configurations will help us explain the bonding patterns of the elements. See the two sections on our Web site that are related to this section:

Internet: Electron Configurations

Internet: Abbreviated Electron Configurations

Internet: Elements with Electron Configurations Other Than Predicted

Chapter 11 Map



Chapter Checklist

- ☐ Read the Review Skills section. If there is any skill mentioned that you have not yet mastered, review the material on that topic before reading this chapter.
- ☐ Read the chapter quickly before the lecture that describes it.
- ☐ Attend class meetings, take notes, and participate in class discussions.
- ☐ Work the Chapter Exercises, perhaps using the Chapter Examples as guides.
- ☐ Study the Chapter Glossary and test yourself on our Web site:

  Internet: Glossary Quiz

- ☐ Study all of the Chapter Objectives. You might want to write a description of how you will meet each objective. (Although it is best to master all of the objectives, the following objectives are especially important because they pertain to skills that you will need while studying other chapters of this text: 12 and 13.)

- ☐ Reread the Study Sheets in this chapter and decide whether you will use them or some variation on them to complete the tasks they describe.

  Sample Study Sheet 11.1: Writing Complete Electron Configurations and Orbital Diagrams for Uncharged Atoms

  Sample Study Sheet 11.2: Abbreviated Electron Configurations

- ☐ To get a review of the most important topics in the chapter, fill in the blanks in the Key Ideas section.
- ☐ Work all of the selected problems at the end of the chapter, and check your answers with the solutions provided in this chapter of the study guide.
- ☐ Ask for help if you need it.

Web Resources

Internet: Electron Configurations

Internet: Abbreviated Electron Configurations

Internet: Elements with Electron Configurations Other Than Predicted

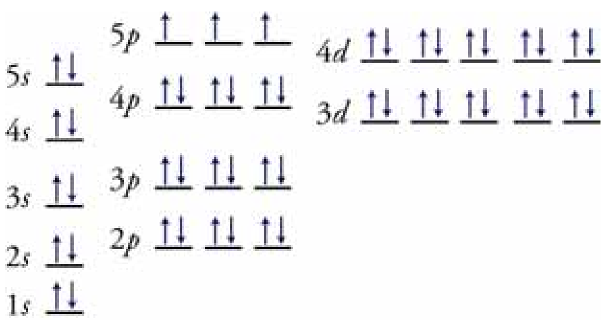
Internet: Glossary Quiz

Exercises Key

✍ Exercise 11.1 - Electron Configurations and Orbital Diagrams:

Write the complete electron configuration and draw an orbital diagram for antimony, Sb. *(Objs 12 & 13)*

$1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^6\ 4s^2\ 3d^{10}\ 4p^6\ 5s^2\ 4d^{10}\ 5p^3$



✍ Exercise 11.2 - Abbreviated Electron Configurations:

Write abbreviated electron configurations for (a) rubidium, Rb, (b) nickel, Ni, and (c) bismuth, Bi. *(Obj 14)*

a. rubidium, Rb **[Kr] $5s^1$**

b. nickel, Ni **[Ar] $4s^2\ 3d^8$**

b. bismuth, Bi **[Xe] $6s^2\ 4f^{14}\ 5d^{10}\ 6p^3$**

Review Questions Key

1. Describe the nuclear model of the atom.

   Protons and neutrons are in a tiny core of the atom called the nucleus, which has a diameter of about 1/100,000 the diameter of the atom. The position and motion of the electrons are uncertain, but they generate a negative charge that is felt in the space that surrounds the nucleus.

2. Describe the relationship between stability and potential energy.

   Increased stability of the components of a system leads to decreased potential energy, and decreased stability of the components of a system leads to increased potential energy.

Key Ideas Answers

3. The electron is extremely tiny, and modern physics tells us that **strange** things happen in the realm of the very, very small.
5. Modern physics tells us that it is **impossible** to know **exactly** where an electron is and what it is doing.
7. In order to accommodate the uncertainty of the electron's position and motion, scientists talk about where the electron **probably** is within the atom, instead of where it **definitely** is.
9. In the wave view, an electron has an effect on the space around it that can be described as a wave of **negative charge** varying in its intensity.
11. Just as the **intensity of movement** of a guitar string can vary, so can the **intensity of the negative charge** of the electron vary at different positions outside the nucleus.
13. As in the case of the guitar string, only certain waveforms are **possible** for the electron in an atom.
15. The information calculated for the hydrogen electron is used to describe the **other elements** as well.
17. The allowed waveforms for the electron are also called orbitals. Another definition of orbital is as the volume that contains a given **high percentage** of the electron charge. An orbital can also be defined as the **volume** within which an electron has a high probability of being found.
19. In the particle view, the electron **cloud** can be compared to a multiple-exposure photograph of the electron.
21. Because the **strength** of the attraction between positive and negative charges decreases with increasing distance between the charges, an electron is more strongly attracted to the nucleus and therefore is more stable when it has the smaller 1*s* waveform than when it has the larger 2*s* waveform. Increased stability is associated with **decreased** potential energy, so a 1*s* electron has lower potential energy than a 2*s* electron.
23. After the electron is excited from the 1*s* orbital to the 2*s* orbital, it **spontaneously returns** to its lower-energy 1*s* form.
25. Orbitals that have the same potential energy, the same size, and the same shape are in the same **sublevel**.

27. Note that the first principal energy level has one sublevel, the second has two, the third has three, and the fourth has four. If ***n*** is the number associated with the principal energy level, each principal energy level has *n* sublevels.
29. None of the known elements in its ground state has any electrons in a principal energy level higher than the **seventh**.
31. We can visualize the two electrons in a helium atom as **spinning** in opposite directions.
33. An atomic orbital may contain **2** electrons at most, and the electrons must have different **spins**.
35. The highest-energy electrons for all of the elements in groups 1 (1A) and 2 (2A) in the periodic table are in ***s* orbitals**.
37. The last electrons to be added to an orbital diagram for the atoms of the transition metal elements go into ***d*** orbitals.

Problems Key

Section 11.1 The Mysterious Electron

39. Explain why, in theory, a guitar string can vibrate with an infinite number of possible waveforms but not all waveforms are possible. *(Obj 2)*

    The possible waveforms are limited by the fact that the string is tied down and cannot move at the ends, but there are an infinite number of possible waveforms that allow the string to remain stationary at the ends.

41. Describe the 1*s* orbital in a hydrogen atom in terms of negative charge and in terms of the electron as a particle. *(Obj 4)*

    The negative-charge distribution of an electron in a 1*s* orbital of a hydrogen atom looks like the image in Figure 11.3 of the text. The cloud is pictured as surrounding the nucleus and represents the variation in the intensity of the negative charge at different positions outside the nucleus. The negative charge is most intense at the nucleus and diminishes with increasing distance from the nucleus. The variation in charge intensity for this waveform is the same in all directions, so the waveform is a sphere. Theoretically, the charge intensity decreases toward zero as the distance from the nucleus approaches infinity. The 1*s* orbital can be described as a sphere that contains a high percentage (for example 90% or 99%) of the charge of the 1*s* electron.

    According to the particle interpretation of the wave character of the electron, a 1*s* orbital is a surface within which we have a high probability of finding the electron. In the particle view, the electron cloud can be compared to a multiple-exposure photograph of the electron (once again, we must resort to an analogy to describe electron behavior). If we were able to take a series of sharply focused photos of an electron over a period of time without advancing the film, our final picture would look like the image in Figure 11.5 of the text. We would find a high density of dots near the nucleus (because most of the times when the shutter snaps, the electron would be near the nucleus) and a decrease in density with increasing distance from the nucleus (because some of the times the shutter snaps, the electron would be farther away from the nucleus). This arrangement of dots would bear out the wave equation's prediction of the probability of finding the electron at any given distance from the nucleus.

43. Describe a 2*s* orbital for a hydrogen atom. *(Obj 6)*

The 2*s* orbital for an electron in a hydrogen atom is spherical like the 1*s* orbital, but it is a larger sphere. For an electron in the 2*s* orbital, the charge is most intense at the nucleus, it diminishes in intensity to a minimum with increasing distance from the nucleus, it increases again to a maximum, and finally it diminishes again. The section of the 2*s* orbital where the charge intensity goes to zero is called a node. Figure 11.7 of the text, shows cutaway, quarter section views of the 1*s* and 2*s* orbitals.

45. Which is larger, a 2*p* orbital or a 3*p* orbital? Would the one electron in a hydrogen atom be more strongly attracted to the nucleus in a 2*p* orbital or in a 3*p* orbital? Would the electron be more stable in a 2*p* orbital or in a 3*p* orbital? Would the electron have higher potential energy when it is in a 2*p* orbital or a 3*p* orbital?

The 3*p* orbital is larger than the 2*p* orbital. Because the average distance between the positively charged nucleus and the negative charge of an electron in a 2*p* orbital would be less than for an electron in a 3*p* orbital, the attraction between a 2*p* electron and the nucleus would be stronger. This makes an electron in a 2*p* orbital more stable and gives it lower potential energy than an electron in a 3*p* orbital.

47. Describe the three 2*p* orbitals for a hydrogen atom. *(Obj 8)*

The three 2*p* orbitals are identical in shape and size, but each is 90° from the other two. Because they can be viewed as being on the x, y and z axes of a three-dimensional coordinate system, they are often called the $2p_x$, $2p_y$, and $2p_x$ orbitals. One electron with a 2*p* waveform has its negative charge distributed in two lobes on opposite sides of the nucleus. Figures 11.8 and 11.9 of the text, show two ways to visualize these orbitals, and Figure 11.10 of the text, shows the three 2*p* orbitals together.

50. How many orbitals are there in the 3*p* sublevel for the hydrogen atom? **3**

52. How many orbitals are there in the third principal energy level for the hydrogen atom?

There are **nine** orbitals in the third principal energy level: one in the 3*s* sublevel, three in the 3*p* sublevel, and five in the 3*d* sublevel.

54. Which of the following sublevels do not exist?

a. 5*p* **exists**

b. 2*s* **exists**

c. 3*f* **not exist**

d. 6*d* **exists**

Section 11.2 Multi-Electron Atoms

57. What is the maximum number of electrons that can be placed in a 3*p* orbital? in a 3*d* orbital?

    two The maximum number of electrons in *any* orbital is 2.

59. What is the maximum number of electrons that can be placed in a 3*p* sublevel? in a 3*d* sublevel?

    The maximum number of electrons in any *p* sublevel is **six**. The maximum number of electrons in any *d* sublevel is **ten**.

61. What is the maximum number of electrons that can be placed in the third principal energy level?

    The third principal energy level can hold up to 18 electrons: two in the 3*s*, six in the 3*p*, and ten in the 3*d*.

63. For each of the following pairs, identify the sublevel that is filled first.

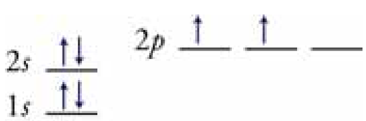
    a. 2*s* or 3*s* **2*s***   c. 3*d* or 4*s* **4*s***

    b. 3*p* or 3s **3*s***   d. 4*f* or 6*s* **6*s***

65. Write the complete electron configuration and orbital diagram for each of the following. *(Objs 11 & 12)*

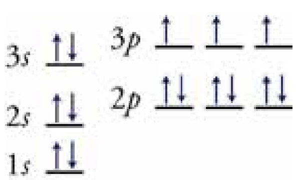
    a. carbon, C

    $1s^2\ 2s^2\ 2p^2$



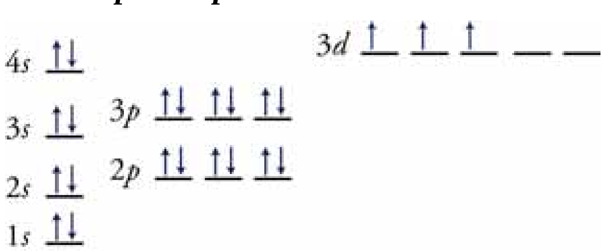
    b. phosphorus, P

    $1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^3$



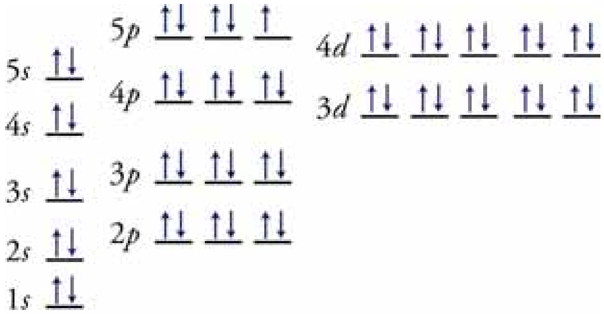
    c. vanadium, V

    $1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^6\ 4s^2\ 3d^3$



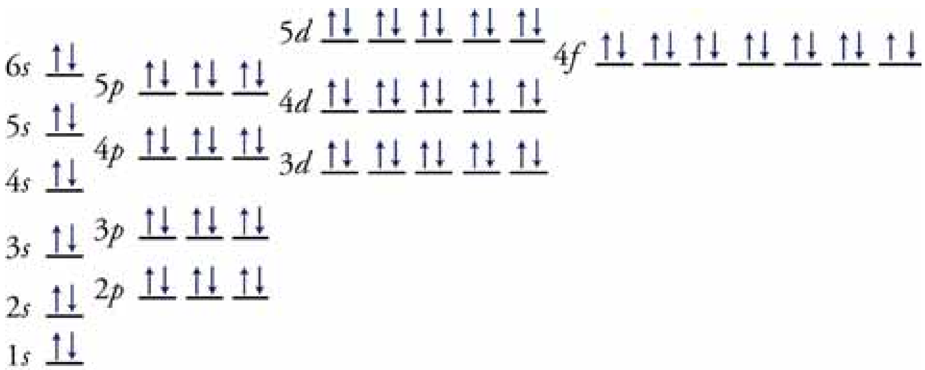
d. iodine, I

$1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^6\ 4s^2\ 3d^{10}\ 4p^6\ 5s^2\ 4d^{10}\ 5p^5$



e. mercury, Hg

$1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^6\ 4s^2\ 3d^{10}\ 4p^6\ 5s^2\ 4d^{10}\ 5p^6\ 6s^2\ 4f^{14}\ 5d^{10}$



67. Which element is associated with each of the ground state electron configurations listed below?
    - a. $1s^2\ 2s^2$ **Be**
    - b. $1s^2\ 2s^2\ 2p^6\ 3s^1$ **Na**
    - c. $1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^6\ 4s^2\ 3d^{10}\ 4p^5$ **Br**
    - d. $1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^6\ 4s^2\ 3d^{10}\ 4p^6\ 5s^2\ 4d^{10}\ 5p^6\ 6s^2\ 4f^{14}\ 5d^{10}\ 6p^2$ **Pb**

69. Would the following electron configurations represent ground states or excited states?
    - a. $1s^2\ 2s^1\ 2p^5$ **excited**
    - b. $1s^2\ 2s^2\ 2p^4$ **ground**
    - c. $1s^2\ 2s^2\ 2p^4\ 3s^1$ **excited**
    - d. $1s^2\ 2s^2\ 2p^5$ **ground**

71. Write the abbreviated electron configurations for each of the following. *(Obj 13)*
    - a. fluorine, F **[He] $2s^2\ 2p^5$**
    - b. silicon, Si **[Ne] $3s^2\ 3p^2$**
    - c. cobalt, Co **[Ar] $4s^2$ $3d^7$**
    - d. indium, In **[Kr] $5s^2$ $4d^{10}$ $5p^1$**
    - e. polonium, Po **[Xe] $6s^2\ 4f^{14}$ $5d^{10}$ $6p^4$**

Additional Problems

73. Which sublevel contains:
    a. the highest-energy electron for francium, Fr? **7*s***
    b. the 25th electron added to an orbital diagram for elements larger than chromium, Cr? **3d**
    c. the 93rd electron added to an orbital diagram for elements larger than uranium, U? **5f**
    d. the 82nd electron added to an orbital diagram for elements larger than lead, Pb? **6p**
75. What is the first element on the periodic table to have
    b. an electron in the 3*p* sublevel. **Al**
    c. a filled 4*s* sublevel. **Ca**
    d. a half-filled 3*d* sublevel. **Mn**
77. Which pair of the following ground-state, abbreviated electron configurations corresponds to elements in the same group on the periodic table? What elements are they? What is the name of the group to which they belong?
    a. [Ne] $3s^2$
    b. [Ar] $4s^2\ 3d^{10}$
    c. [Kr] $5s^2$
    d. [Xe] $6s^2\ 4f^{14}\ 5d^{10}\ 6p^1$

    The pair "a" and "c" represent the alkaline earth metals magnesium and strontium.
79. What is the maximum number of electrons in each of the following?
    a. the 8*j* sublevel **30**
    b. a 6*h* orbital **2**
    c. the n = 8 principle energy level **128**
82. Write the expected abbreviated electron configuration for the as-yet-undiscovered element with the atomic number of 121. Use Uuo for the symbol of the noble gas below xenon, Xe. (*Hint*: See Figure 11.17.)

    [Uuo] $8s^2\ 5g^1$ or [Uuo] $5g^1\ 8s^2$