Atoms and Materials for Engineering

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An engineer should have some knowledge of atoms and the materials formed by combinations of atoms. As aspiring engineers, I thought it would be good to introduce you to this subject. We will be talking about different materials used in engineering from time to time and this paper may help you understand this subject. Some of the topics I will discuss are covered in much greater detail in high school chemistry and physics and especially the same courses at the college level. In this paper we can only cover the topic at a very elementary level.

Atoms

We have already learned that atoms are the basic building blocks of matter. The main parts of the atom (Figure 1) are the **nucleus** and **electrons**. The nucleus occupies the center of the atom and the electrons occupy orbitals that surround the nucleus. The nucleus contains two kinds of particles: **protons** and **neutrons**. Protons carry a positive electric charge, electrons carry a negative electric charge and neutrons are not electrically charged. Positive and negative charges are attractive and it is this attractive force that keeps electrons bound in orbitals surrounding the nucleus.

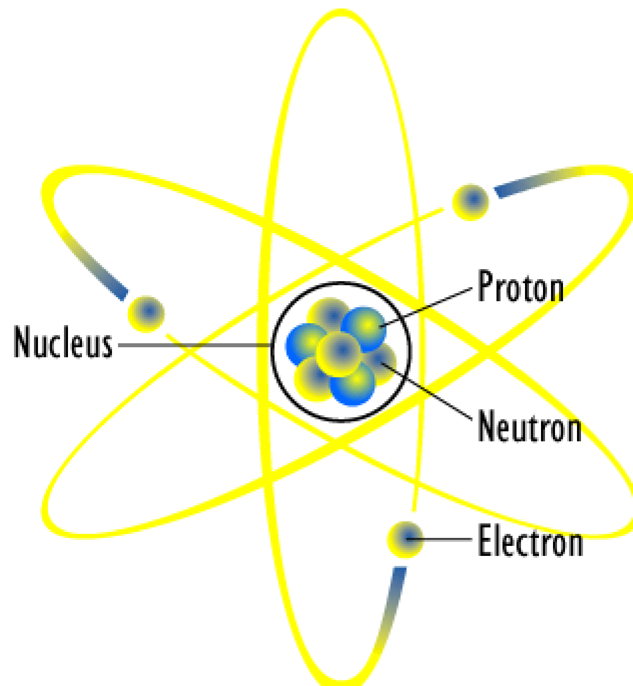


Figure 1 simplified diagram of an atom

The world as we experience it with our eyes is much different than the world we would know if our eyes would allow us to see electrons and protons. You must understand that the drawing of the atom in Figure 1 is not really the way an atom is structured. It is a very simplified model that we can use as we attempt to begin understanding the atom. In reality atoms are structured in strange ways that are hard to understand. In fact, many scientists in the early 20th century struggled very hard to build an accurate model of the atom.

The electron was the first subatomic particle to be discovered. The discovery is credited to Joseph John Thomson. His discovery was the result of work done in 1897. He was awarded the Nobel Prize in Physics in 1906 for his discovery of the electron and for work on conduction of electricity in gases. You can read more about him at this web site: http://en.wikipedia.org/wiki/Jj_thomson

In 1917 Ernest Rutherford discovered the proton. The discovery of the neutron came quite a few years later, in 1932. It is interesting to note that the discovery was made by James Chadwick, a scientist who worked in Ernest Rutherford's laboratory. This might all seem like ancient history to you but keep in mind that the discovery of the neutron occurred only 17 years before my birth. It does not seem that long ago to me! You can read more about Ernest Rutherford at this link: http://en.wikipedia.org/wiki/Ernest_Rutherford

In 1909 Ernest Rutherford discovered the nucleus with the help of Hans Geiger and Ernest Marsden. It is really hard to imagine just how small the nucleus is compared to the size of the electron orbitals that surround the nucleus. After studying the experimental results, Rutherford estimated the diameter of a gold nucleus to be at least several thousand times less than the diameter of the gold atom!

Obviously our drawing of the atom in Figure 1 does not show the nucleus to proper scale. If we did draw it properly, then it would be so small that we could not even see it. There are other problems with our drawing in Figure 1. The electrons do not orbit around the nucleus like planets around the Sun. Electrons occupy spaces around the nucleus called orbitals. There are a number of different kinds of orbitals, depending on the kind of atom.

We should start with the simplest kind of atom, hydrogen. Most hydrogen atoms contain one proton in the nucleus, no neutrons in the nucleus and one electron (there are a very low percentage of hydrogen atoms that contain either one or two neutrons in addition to the one proton). The electron occupies an orbital that is spherically shaped. Suppose we use a basketball as our model of the hydrogen atom. The outside skin of the ball would define the boundary of the orbital. The tiny nucleus would be located inside the ball at the center of the orbital. The electron occupies the space inside the orbital boundary. Rarely, the electron can also extend outside the orbital boundary. In fact, we define the orbital as the space occupied by the electron over a significant percentage of time, say 99%. In other words, we can expect to find the electron occupying only the space inside the orbital 99% of the time if we choose that figure as the definition of the orbital boundary.

In the case of planets orbiting around the Sun, we can predict the location of a planet in the future because it follows a specific path. We can't do this for an electron. In a sense, an electron is everywhere inside the orbital at any given instant of time. If we think of the electron only in terms of a particle, this does not make any sense. If it is a particle, then it must have a specific location inside the orbital. However, the electron has properties of a wave in addition to properties of a particle. Thinking about an electron as a wave is more difficult than thinking about it as a particle. If we say that an electron is a wave, then we can understand why it occupies all of the orbital at any given moment in time. We can say that the electron exists in the orbital as a **standing** wave.

Each orbital can contain a maximum of two electrons. The next larger kind of atom, helium, contains 2 protons and 2 electrons (also usually 2 neutrons, but we will ignore the neutrons). The two electrons of helium occupy the same kind of spherical orbital found in hydrogen. We call this orbital the **1s** orbital.

Lithium is the next atom, containing 3 protons and 3 electrons. Since we can only have 2 electrons in each orbital, we need a second orbital in lithium to house the third electron. This orbital is also spherical in shape, but larger than the 1s orbital. Thus, lithium has two orbitals, one like hydrogen and helium and an additional spherical orbital which is larger, called **2s**.

Things start to get more interesting when we study the boron atom (5 protons and 5 electrons). Now we find an additional orbital that is not spherical-shaped. Rather than try and describe the shape, it is better to just take a look at Figure 2. This kind of orbital is named a **p orbital**. The spherical orbitals we have already mentioned are called **s orbitals**. The arrow in Figure 2 indicates the position of the nucleus, which is too small for us to see at this scale. The p orbital has two parts (one colored red the other colored blue). This may seem confusing. There are not 2 orbitals in the drawing, only one. But it has two parts. I will not explain the details of the two parts because it is an advanced topic. However, you should understand that the electron actually occupies both parts of the orbital.

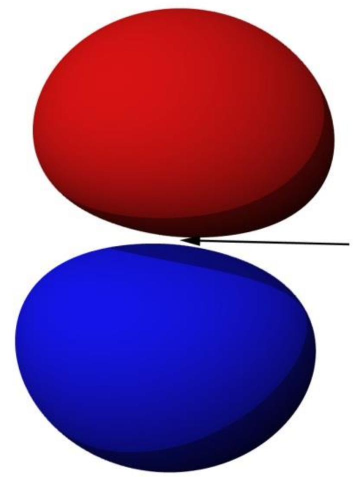


Figure 2 p orbital

In the early 20th century scientists discovered that they could not explain the behavior of electrons if they were just considered particles. Some of the behavior could only be explained if electrons behaved like waves. Erwin Schrödinger developed the wave equation that can be used to understand the wave behavior of electrons. This is an advanced topic taught in college courses. You can learn more about Schrödinger at this link: http://en.wikipedia.org/wiki/Erwin_Schr%C3%B6dinger

As we look at atoms with high numbers of protons and electrons, we find many additional orbitals. For example, copper has 29 protons and 29 electrons. Remembering that a maximum of two electrons can fit in each orbital, that means that the copper atom has 15 orbitals, 14 full and one half full. In addition to many orbitals of the s and p types, there are the additional d-type orbitals (Figure 3). Notice that the d orbital has four parts (the arrow marks the position of the nucleus). There is an additional shape for a d-type orbital which I will not show here.

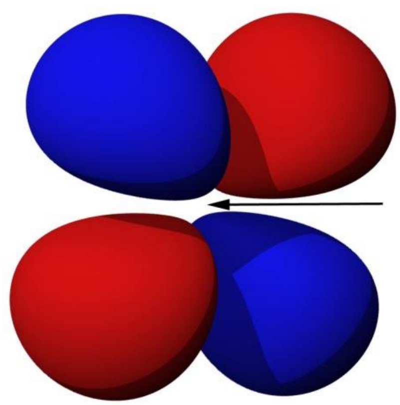


Figure 3 d orbital

Still larger atoms, like uranium, have an additional class of orbitals called f orbitals with even more complicated shapes. I will not include a picture of those here. The important thing to understand is that electrons don't circle around the nucleus like planets around the Sun. Instead, they occupy a fascinating array of different orbitals of different shapes.

Periodic Table of the Elements

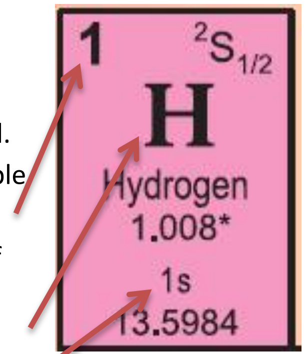


Figure 4 hydrogen in periodic table

At the end of this paper I have included a periodic table of the elements. We have already been talking about elements but I have not mentioned the word element until now. Hydrogen is an element. Copper is an element. There are 90 elements that occur naturally on Earth and 24 which have been synthesized. The first element, named hydrogen, is found at the upper left corner of the table (Figure 4). In the upper left corner of the rectangle for hydrogen we see the number one, the atomic number. The atomic number indicates the number of protons in the nucleus. Hydrogen has the atomic number of 1 because it has one proton in its nucleus. The chemical symbol for hydrogen is H, which is printed in large size. Also notice the **1s** printed near the bottom of the rectangle. That is the electronic configuration. Hydrogen has only one orbital, the 1s orbital, and has only one electron occupying the orbital.

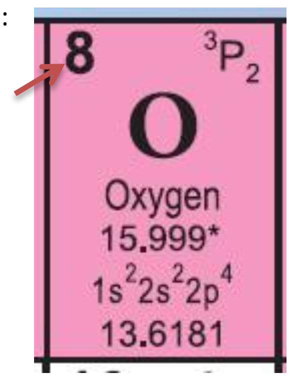
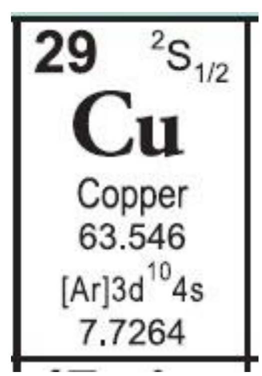
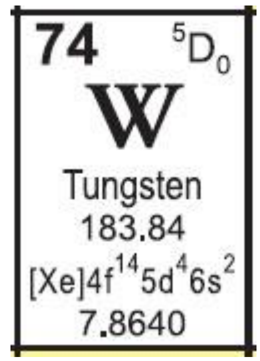


Figure 5 oxygen

Now let us take a look at an element that you should have some familiarity with: oxygen. Oxygen is an important part of the atmosphere on Earth. Your life depends in part on the oxygen you take into your lungs. The atomic number of oxygen is eight because it has 8 protons in its nucleus. The electronic configuration for oxygen is $1s^22s^22p^4$. Oxygen has 2 s-type orbitals. The 1s orbital is smaller than the 2s orbital. Both of the s orbitals contain 2 electrons. The oxygen also has some p orbitals but the number is not given in the table entry. We only know that they are second-level p orbitals (2p). The number 4 after the p indicates that there are 4 electrons in 2p orbitals. It is expected that we already know there are a maximum of three p orbitals at level 2, two contain one electron each and the other has 2 electrons. Of course you have not had high school chemistry yet, so you should not be expected to know that.



Now let us take a look at copper, an important element, because it is commonly used as the metal for electrical conductors, among other things. The symbol for copper is Cu and it is atomic number 29, meaning it has 29 protons in its nucleus. Here we see the electron configuration is [Ar] $3d^{10}4s$. The copper atom has many orbitals and we use a shorcut here to make the designation shorter. The [Ar] represents argon, which you should find as atomic number 18 on the table. So we take the electronic configuration of argon and add $3d^{10}4s$ to it. When we look at argon on the table its electron configuration is listed as [Ne] $3s^23p^6$. The [Ne] represents neon, atomic number 10. It has the electron configuration $1s^22s^22p^6$. Therefore, the electronic configuration of copper, written out in long form, is: $1s^22s^22p^63s^23p^63d^{10}4s$. At energy level 1, there are 2 electrons in the 1s orbital. At energy level 2 there are 2 electrons in the 2s orbital and 6 electrons, two each, in three 2p orbitals. At energy level 3 there are 2 electrons in the 3s orbital, 6 electrons, two each, in three 3p orbitals, 10 electrons, two each, in 5 3d orbitals and one electron in the fourth energy level 4s orbital. If you add all of those electron numbers together, you should get 29.



In lesson one we have been working with light bulbs that contain tungsten filaments. Well, it just so happens that tungsten is an element, atomic number 74. It has 74 protons in its nucleus! I won't make you read through the electronic configuration of tungsten. However, notice that it does have 14 electrons in 4f orbitals. Why is the symbol W for tungsten? Well, if you look carefully at the table you will find additional strange symbols like Ag for silver and Au for gold. Some of the symbols come from alternate names for the element. For example, tungsten is called wolfram in many countries in Europe, which is the reason the letter W is used for the atomic symbol. In Latin the word for gold is aurum and the word for silver is argentum, which are the origins of the chemical symbols used.

Atomic Bonds

As interesting as atoms are individually, the really interesting stuff comes when we study how atoms combine with each other. This is what the subject of chemistry is all about. It is a topic that is challenging to study and one we can only mention in a passing manner. Nearly all atoms ocurr connected to at least one other atom. The connections are made by atomic bonds. There are three important kinds of primary atomic bonds: 1) **ionic** 2) **covalent** 3) **metallic**. To really understand each kind, you would need to read many pages of explanation. So let us just try for some simple descriptions here.

I**onic bonds** occur between two different kinds of atoms, where one atom donates an electron or electrons to other atoms. We can take the example of ordinary table salt (sodium chloride) which is a combination of the elements sodium (symbol Na) and chlorine (symbol Cl). The nature of the sodium atom is such that it does not mind at all giving up its lone electron in the outer 3s orbital. The chlorine atom has a strong desire to collect one electron, which it gets from the sodium atom. With the exchange of the electron, both atoms become electrically charged. Sodium has a positive charge because it now has one more proton than electron (11 protons = 11 plus charges, 10 electrons = 10 negative charges, and the net charge is then plus one). And chlorine has a negative charge because it has one more electron than it has protons. Remember that unlike charges attract each other. The positively charged sodium and negatively charged chlorine are attracted to each other and form an ionic bond. Atoms that are charged are called ions.

Much of chemistry is concerned with the second kind of atomic bond, the **covalent bond**. In this kind of bond atoms share electrons in pairs. That is, two atoms share two electrons, one from each atom. The sharing of an electron pair results in one covalent bond. It is also possible for atoms to share more than one pair. For example, the nitrogen in Earth's atmosphere is found in the form of molecules containing two atoms of nitrogen. The two atoms are connected with three covalent bonds. Oxygen in Earth's atmosphere is also present as molecules containing two atoms of oxygen connected with two covalent bonds. Water is a molecule containing two atoms of hydrogen and one atom of oxygen. The oxygen atom forms one covalent bond with each of the hydrogen atoms.

When we study electricity, we are particularly interested in the nature of the **metallic bonds** that form between atoms such as copper. Unlike covalent bonds, where electrons are only shared by two atoms, metal atoms joined by metallic bonding have “delocalized” electrons. That means that the outer electrons are shared rather freely between many atoms. It is the nature of the metallic bond that allows electrons to flow freely through a metal. All we need to do is apply a voltage to the metal to encourage the electrons to flow in a specific direction.

Abundance of elements in Earth’s crust

While there are 90 elements naturally occuring on Earth, the abundance of the elements varies dramatically. The cost of various materials used in engineering will depend in part on the availability of required elements. Iron (symbol Fe) is the main component of steel. The Earth’s crust is 6.3% Fe by weight. While the properites of iron are important in dictating its use as a metal in engineered products, its abundance in Earth’s crust is also an important factor. Aluminum (symbol Al) is another important metal in engineered products and has an abundance of 8.2% in the Earth’s crust. In contrast, the abundance of gold in Earth’s crust is about 0.003 parts per milllion or 0.0000003%. That is why we call gold a precious metal and the reason why it is so expensive.

Nearly three fourths of the Earth’s crust is due to only two elements, which may come as a surprise. Oxygen’s abundance in the crust is 46%, which may be the biggest surprise. Oxygen is a significant component of many of the major minerals that make up the Earth’s crust. Oxygen in pure form is a gas, just as we find it in Earth’s atmosphere. But oxygen bonds readily to other elements, the mixture of which can be solid (crustal minerals) or liquid (water) at room temperature.

Silicon (symbol Si) is found at about 27% in the crust and is another common element found in minerals of the crust. The crystal mineral named quartz is composed of silicon and oxygen in the proportion of one silicon atom to two oxygen atoms. We can call this silicon dioxide and write the chemical formula as SiO_2. Window glass is an amorphous material (*i.e.,* not a crystal) that is primarily silicon dioxide with smaller amounts of other oxygen compounds containing the elements calcium (Ca) and magnesium (Mg) as well as even smaller amounts of a few more elements. Silicon is the primary element used in the manufacture of semiconductors, which have revolutionized the electronics industry. The integrated chips found in computers are manufactured from wafers of pure silicon in the crystalline form to which very small amounts of other elements have been added in a very precise manner. The added elements are known as dopants.

Here are some additional elements of interest. Titanium (Ti) is found at 0.7% in the crust. It is used as a high tech metal due to its high strength relative to its light weight. Tungsten (W) is found at one part per million in the crust. It is used as a filament in incandescent light bulbs due in part to its unusually high melting point. Copper (Cu) is found at 60 parts per million in the crust. It has very good electrical conductivity properties and is a common metal used for electrical wire. However, copper is relatively expensive compared to aluminum, which is why aluminum is commonly used in wires of large diameter where large amounts of current must be carried. In those cases the slightly poorer conductivity of aluminum is outweighed by its low material cost.

Manufacture of metals

Metals are made by extracting the metallic elements from minerals in the Earth's crust. The first step in the process in called mining, which essentially involves the removal of material from the ground. Here I will list some examples of minerals found in the Earth's crust from which metals can be extracted. Magnetite is a mineral with the chemical formula Fe_3O_4 (three atoms of iron and four atoms of oxygen), and hematite is Fe_2O_3. When we heat these minerals to a high temperature, in the presence of additional materials, it is possible to extract the iron from the minerals and produce iron metal. Chalcocite is a mineral containing copper and has the chemical formula Cu_2S (two copper atoms and one sulfer atom). Bauxite is an ore from which aluminum can be extracted. Bauxite is a mixture of aluminum-containing minerals such as gibbsite. Gibbsite has the formula $Al(OH)_3$ (one aluminum atom and three OH groups, which are oxygen atoms bonded to hydrogen atoms).

The abundance of metal elements in the Earth's crust is only one factor determing the cost of manufacturing a metal. The mineral deposits need to be concentrated in a location where they can be easily removed from the ground in order for the mining operation to be economically viable. In addition, the processes used to extract the metal must be relatively inexpensive in order to make metals that are affordable.

Metal alloys

Metals made from pure elements often have properites that are not optimum for a specific use in engineered products. For example, pure iorn metal is relatively weak. By adding a small percentage of the element carbon to the iron, the strength of the metal is improved dramatically. We call this kind of metal steel. Steel is used for many things ranging from the manufacture of steel beams used as the skeleton of large buildings to the bodies of automobiles. When we combine different elements together to form a metal, we call it a metal alloy. Steel is a metal alloy.

PERIODIC TABLE
Atomic Properties of the Elements

NIST
National Institute of Standards and Technology
U.S. Department of Commerce

Physical Measurement Laboratory
www.nist.gov/pml

Standard Reference Data
www.nist.gov/srd

Frequently used fundamental physical constants

For the most accurate values of these and other constants, visit physics.nist.gov/constants

1 second = 9 192 631 770 periods of radiation corresponding to the transition between the two hyperfine levels of the ground state of ^{133}Cs

speed of light in vacuum	c	299 792 458 m s^{-1}	(exact)
Planck constant	h	6.626 07 x 10^{-34} J s	($\hbar = h/2\pi$)
elementary charge	e	1.602 177 x 10^{-19} C	
electron mass	m_e	9.109 38 x 10^{-31} kg	
	$m_e c^2$	0.510 999 MeV	
proton mass	m_p	1.672 622 x 10^{-27} kg	
fine-structure constant	α	1/137.035 999	
Rydberg constant	R_∞	10 973 731.569 m^{-1}	
	$R_\infty c$	3.289 841 960 x 10^{15} Hz	
	$R_\infty hc$	13.605 69 eV	
Boltzmann constant	k	1.380 6 x 10^{-23} J K^{-1}	

- Solids
- Liquids
- Gases
- Artificially Prepared

Period	Group 1 IA	2 IIA	3 IIIB	4 IVB	5 VB	6 VIB	7 VIIB	8 VIII	9 VIII	10 VIII	11 IB	12 IIB	13 IIIA	14 IVA	15 VA	16 VIA	17 VIIA	18 VIIIA
1	1 H $^2S_{1/2}$ Hydrogen 1.008* $1s$ 13.5984																	2 He $^1S_0$ Helium 4.002602 $1s^2$ 24.5874
2	3 Li $^2S_{1/2}$ Lithium 6.94* $1s^22s$ 5.3917	4 Be $^1S_0$ Beryllium 9.012182 $1s^22s^2$ 9.3227											5 B $^2P^o_{1/2}$ Boron 10.81* $1s^22s^22p$ 8.2980	6 C $^3P_0$ Carbon 12.011* $1s^22s^22p^2$ 11.2603	7 N $^4S^o_{3/2}$ Nitrogen 14.007* $1s^22s^22p^3$ 14.5341	8 O $^3P_2$ Oxygen 15.999* $1s^22s^22p^4$ 13.6181	9 F $^2P^o_{3/2}$ Fluorine 18.9984032 $1s^22s^22p^5$ 17.4228	10 Ne $^1S_0$ Neon 20.1797 $1s^22s^22p^6$ 21.5645
3	11 Na $^2S_{1/2}$ Sodium 22.98976928 $[Ne]3s$ 5.1391	12 Mg $^1S_0$ Magnesium 24.3050 $[Ne]3s^2$ 7.6462											13 Al $^2P^o_{1/2}$ Aluminum 26.9815386 $[Ne]3s^23p$ 5.9858	14 Si $^3P_0$ Silicon 28.085* $[Ne]3s^23p^2$ 8.1517	15 P $^4S^o_{3/2}$ Phosphorus 30.973762 $[Ne]3s^23p^3$ 10.4867	16 S $^3P_2$ Sulfur 32.06* $[Ne]3s^23p^4$ 10.3600	17 Cl $^2P^o_{3/2}$ Chlorine 35.45* $[Ne]3s^23p^5$ 12.9676	18 Ar $^1S_0$ Argon 39.948 $[Ne]3s^23p^6$ 15.7596
4	19 K $^2S_{1/2}$ Potassium 39.0983 $[Ar]4s$ 4.3407	20 Ca $^1S_0$ Calcium 40.078 $[Ar]4s^2$ 6.1132	21 Sc $^2D_{3/2}$ Scandium 44.955912 $[Ar]3d4s^2$ 6.5615	22 Ti $^3F_2$ Titanium 47.867 $[Ar]3d^24s^2$ 6.8281	23 V $^4F_{3/2}$ Vanadium 50.9415 $[Ar]3d^34s^2$ 6.7462	24 Cr $^7S_3$ Chromium 51.9961 $[Ar]3d^54s$ 6.7665	25 Mn $^6S_{5/2}$ Manganese 54.938045 $[Ar]3d^54s^2$ 7.4340	26 Fe $^5D_4$ Iron 55.845 $[Ar]3d^64s^2$ 7.9025	27 Co $^4F_{9/2}$ Cobalt 58.933195 $[Ar]3d^74s^2$ 7.8810	28 Ni $^3F_4$ Nickel 58.6934 $[Ar]3d^84s^2$ 7.6399	29 Cu $^2S_{1/2}$ Copper 63.546 $[Ar]3d^{10}4s$ 7.7264	30 Zn $^1S_0$ Zinc 65.38 $[Ar]3d^{10}4s^2$ 9.3942	31 Ga $^2P^o_{1/2}$ Gallium 69.723 $[Ar]3d^{10}4s^24p$ 5.9993	32 Ge $^3P_0$ Germanium 72.63 $[Ar]3d^{10}4s^24p^2$ 7.8994	33 As $^4S^o_{3/2}$ Arsenic 74.92160 $[Ar]3d^{10}4s^24p^3$ 9.7886	34 Se $^3P_2$ Selenium 78.96 $[Ar]3d^{10}4s^24p^4$ 9.7524	35 Br $^2P^o_{3/2}$ Bromine 79.904 $[Ar]3d^{10}4s^24p^5$ 11.8138	36 Kr $^1S_0$ Krypton 83.798 $[Ar]3d^{10}4s^24p^6$ 13.9996
5	37 Rb $^2S_{1/2}$ Rubidium 85.4678 $[Kr]5s$ 4.1771	38 Sr $^1S_0$ Strontium 87.62 $[Kr]5s^2$ 5.6949	39 Y $^2D_{3/2}$ Yttrium 88.90585 $[Kr]4d5s^2$ 6.2173	40 Zr $^3F_2$ Zirconium 91.224 $[Kr]4d^25s^2$ 6.6339	41 Nb $^6D_{1/2}$ Niobium 92.90638 $[Kr]4d^45s$ 6.7589	42 Mo $^7S_3$ Molybdenum 95.96 $[Kr]4d^55s$ 7.0924	43 Tc $^6S_{5/2}$ Technetium (98) $[Kr]4d^55s^2$ 7.1194	44 Ru $^5F_5$ Ruthenium 101.07 $[Kr]4d^75s$ 7.3605	45 Rh $^4F_{9/2}$ Rhodium 102.90550 $[Kr]4d^85s$ 7.4589	46 Pd $^1S_0$ Palladium 106.42 $[Kr]4d^{10}$ 8.3369	47 Ag $^2S_{1/2}$ Silver 107.8682 $[Kr]4d^{10}5s$ 7.5762	48 Cd $^1S_0$ Cadmium 112.411 $[Kr]4d^{10}5s^2$ 8.9938	49 In $^2P^o_{1/2}$ Indium 114.818 $[Kr]4d^{10}5s^25p$ 5.7864	50 Sn $^3P_0$ Tin 118.710 $[Kr]4d^{10}5s^25p^2$ 7.3439	51 Sb $^4S^o_{3/2}$ Antimony 121.760 $[Kr]4d^{10}5s^25p^3$ 8.6084	52 Te $^3P_2$ Tellurium 127.60 $[Kr]4d^{10}5s^25p^4$ 9.0097	53 I $^2P^o_{3/2}$ Iodine 126.90447 $[Kr]4d^{10}5s^25p^5$ 10.4513	54 Xe $^1S_0$ Xenon 131.293 $[Kr]4d^{10}5s^25p^6$ 12.1298
6	55 Cs $^2S_{1/2}$ Cesium 132.9054519 $[Xe]6s$ 3.8939	56 Ba $^1S_0$ Barium 137.327 $[Xe]6s^2$ 5.2117	Lanthanides	72 Hf $^3F_2$ Hafnium 178.49 $[Xe]4f^{14}5d^26s^2$ 6.8251	73 Ta $^4F_{3/2}$ Tantalum 180.94788 $[Xe]4f^{14}5d^36s^2$ 7.5496	74 W $^5D_0$ Tungsten 183.84 $[Xe]4f^{14}5d^46s^2$ 7.8640	75 Re $^6S_{5/2}$ Rhenium 186.207 $[Xe]4f^{14}5d^56s^2$ 7.8335	76 Os $^5D_4$ Osmium 190.23 $[Xe]4f^{14}5d^66s^2$ 8.4382	77 Ir $^4F_{9/2}$ Iridium 192.217 $[Xe]4f^{14}5d^76s^2$ 8.9670	78 Pt $^3D_3$ Platinum 195.084 $[Xe]4f^{14}5d^96s$ 8.9588	79 Au $^2S_{1/2}$ Gold 196.966569 $[Xe]4f^{14}5d^{10}6s$ 9.2256	80 Hg $^1S_0$ Mercury 200.59 $[Xe]4f^{14}5d^{10}6s^2$ 10.4375	81 Tl $^2P^o_{1/2}$ Thallium 204.38* $[Hg]6p$ 6.1083	82 Pb $^3P_0$ Lead 207.2 $[Hg]6p^2$ 7.4167	83 Bi $^4S^o_{3/2}$ Bismuth 208.98040 $[Hg]6p^3$ 7.2855	84 Po $^3P_2$ Polonium (209) $[Hg]6p^4$ 8.414	85 At $^2P^o_{3/2}$ Astatine (210) $[Hg]6p^5$ 9.350	86 Rn $^1S_0$ Radon (222) $[Hg]6p^6$ 10.7485
7	87 Fr $^2S_{1/2}$ Francium (223) $[Rn]7s$ 4.0727	88 Ra $^1S_0$ Radium (226) $[Rn]7s^2$ 5.2784	Actinides	104 Rf $^3F_2$ Rutherfordium (265) $[Rn]5f^{14}6d^27s^2$ 6.01	105 Db $^4F_{3/2}$ Dubnium (268) $[Rn]5f^{14}6d^37s^2$ 6.8	106 Sg Seaborgium (271) $[Rn]5f^{14}6d^47s^2$ 7.8	107 Bh Bohrium (270) $[Rn]5f^{14}6d^57s^2$ 7.7	108 Hs Hassium (277) $[Rn]5f^{14}6d^67s^2$ 7.6	109 Mt Meitnerium (276)	110 Ds Darmstadtium (281)	111 Rg Roentgenium (280)	112 Cn Copernicium (285)	113 Uut Ununtrium (284)	114 Fl Flerovium (289)	115 Uup Ununpentium (288)	116 Lv Livermorium (293)	117 Uus Ununseptium (294)	118 Uuo Ununoctium (294)

Lanthanides	57 La $^2D_{3/2}$ Lanthanum 138.90547 $[Xe]5d6s^2$ 5.5769	58 Ce $^1G^o_4$ Cerium 140.116 $[Xe]4f5d6s^2$ 5.5386	59 Pr $^4I^o_{9/2}$ Praseodymium 140.90765 $[Xe]4f^36s^2$ 5.473	60 Nd $^5I_4$ Neodymium 144.242 $[Xe]4f^46s^2$ 5.5250	61 Pm $^6H^o_{5/2}$ Promethium (145) $[Xe]4f^56s^2$ 5.582	62 Sm $^7F_0$ Samarium 150.36 $[Xe]4f^66s^2$ 5.6437	63 Eu $^8S^o_{7/2}$ Europium 151.964 $[Xe]4f^76s^2$ 5.6704	64 Gd $^9D^o_2$ Gadolinium 157.25 $[Xe]4f^75d6s^2$ 6.1498	65 Tb $^6H^o_{15/2}$ Terbium 158.92535 $[Xe]4f^96s^2$ 5.8638	66 Dy $^5I_8$ Dysprosium 162.500 $[Xe]4f^{10}6s^2$ 5.9391	67 Ho $^4I^o_{15/2}$ Holmium 164.93032 $[Xe]4f^{11}6s^2$ 6.0215	68 Er $^3H_6$ Erbium 167.259 $[Xe]4f^{12}6s^2$ 6.1077	69 Tm $^2F^o_{7/2}$ Thulium 168.93421 $[Xe]4f^{13}6s^2$ 6.1843	70 Yb $^1S_0$ Ytterbium 173.054 $[Xe]4f^{14}6s^2$ 6.2542	71 Lu $^2D_{3/2}$ Lutetium 174.9668 $[Xe]4f^{14}5d6s^2$ 5.4259
Actinides	89 Ac $^2D_{3/2}$ Actinium (227) $[Rn]6d7s^2$ 5.3802	90 Th $^3F_2$ Thorium 232.03806 $[Rn]6d^27s^2$ 6.3067	91 Pa $^4K_{11/2}$ Protactinium 231.03588 $[Rn]5f^26d7s^2$ 5.89	92 U $^5L^o_6$ Uranium 238.02891 $[Rn]5f^36d7s^2$ 6.1941	93 Np $^6L_{11/2}$ Neptunium (237) $[Rn]5f^46d7s^2$ 6.2655	94 Pu $^7F_0$ Plutonium (244) $[Rn]5f^67s^2$ 6.0258	95 Am $^8S^o_{7/2}$ Americium (243) $[Rn]5f^77s^2$ 5.9738	96 Cm $^9D^o_2$ Curium (247) $[Rn]5f^76d7s^2$ 5.9914	97 Bk $^6H^o_{15/2}$ Berkelium (247) $[Rn]5f^97s^2$ 6.1978	98 Cf $^5I_8$ Californium (251) $[Rn]5f^{10}7s^2$ 6.2817	99 Es $^4I^o_{15/2}$ Einsteinium (252) $[Rn]5f^{11}7s^2$ 6.3676	100 Fm $^3H_6$ Fermium (257) $[Rn]5f^{12}7s^2$ 6.50	101 Md $^2F^o_{7/2}$ Mendelevium (258) $[Rn]5f^{13}7s^2$ 6.58	102 No $^1S_0$ Nobelium (259) $[Rn]5f^{14}7s^2$ 6.65	103 Lr $^2P^o_{1/2}$ Lawrencium (262) $[Rn]5f^{14}7s^27p$ 4.90

Key:

Atomic Number	58
Ground-state Level	$^1G^o_4$
Symbol	Ce
Name	Cerium
Standard Atomic Weight†	140.116
Ground-state Configuration	$[Xe]4f5d6s^2$
Ionization Energy (eV)	5.5386

†Based upon ^{12}C. () indicates the mass number of the longest-lived isotope.

*IUPAC conventional atomic weights; standard atomic weights for these elements are expressed in intervals; see iupac.org for an explanation and values.

For a description of the data, visit physics.nist.gov/data

NIST SP 966 (March 2013)