Course of lectures «Contemporary Physics: Part2»

Lecture №11

Atomic Physics. Physical Interpretation of the Quantum Numbers. The Exclusion Principle and the Periodic Table. More on Atomic Spectra: Visible and X-Ray. Spontaneous and Stimulated Transitions. Lasers.

Physical Interpretation of the Quantum Numbers

The Orbital Quantum Number *l*

According to quantum mechanics, an atom in a state whose principal quantum number is *n* can take on the following discrete values of the magnitude of the orbital angular momentum:

$$L = \sqrt{\ell(\ell + 1)}\hbar \qquad \ell = 0, 1, 2, \ldots, n - 1$$

Physical Interpretation of the Quantum Numbers

The Orbital Magnetic Quantum Number m_l

$$\vec{\boldsymbol{\mu}} = I\vec{\mathbf{A}}$$

$$U = -\vec{\boldsymbol{\mu}} \cdot \vec{\mathbf{B}}$$

$$L_z = m_\ell \hbar$$

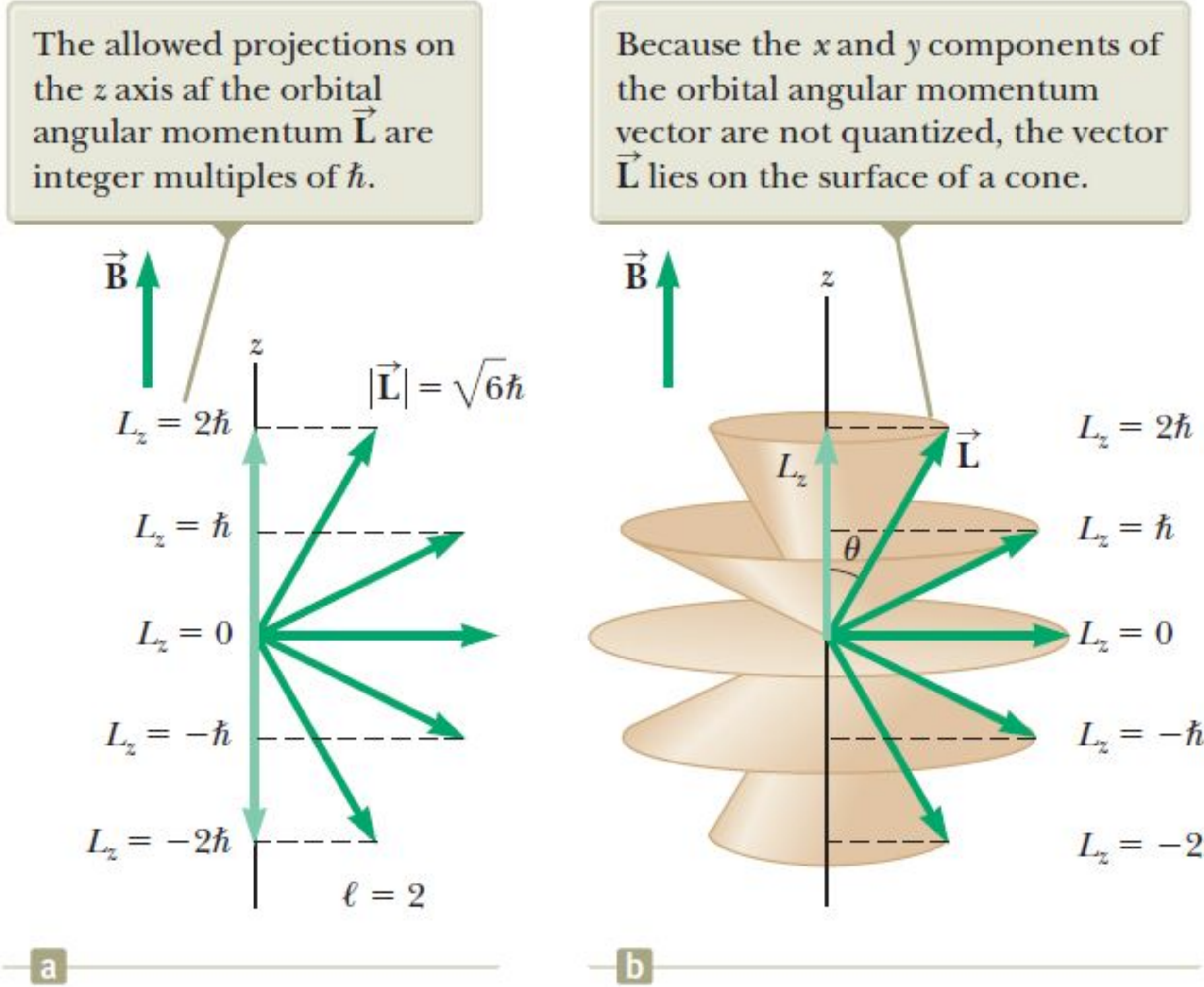
$$\cos\theta = \frac{L_z}{L} = \frac{m_\ell}{\sqrt{\ell(\ell+1)}}$$

$$\mu = \left(\frac{e}{2m_e}\right)L$$

Physical Interpretation of the Quantum Numbers

The Orbital Magnetic Quantum Number m_l

A **vector model that describes space quantization** for the case l=2.

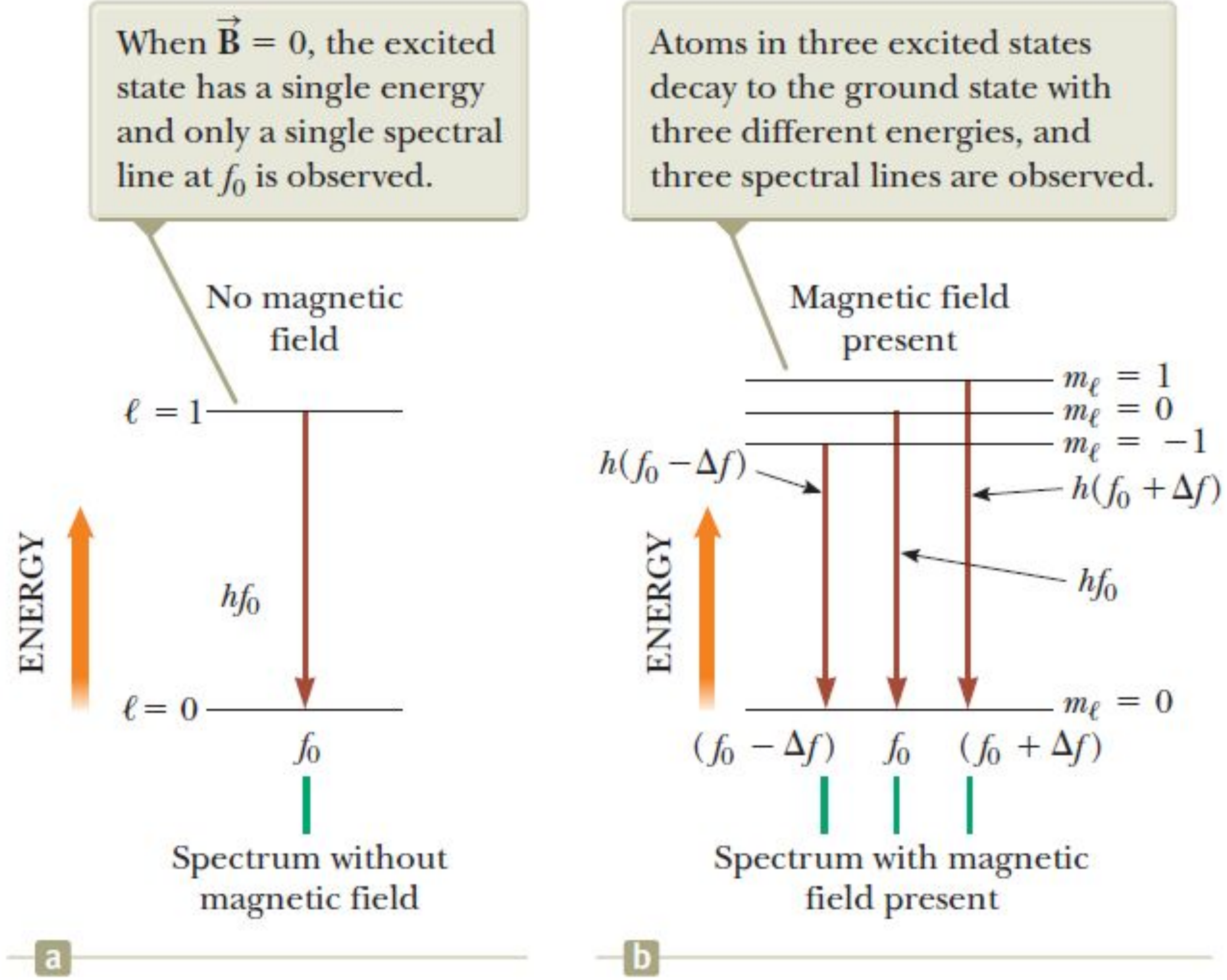


The allowed projections on the *z* axis af the orbital angular momentum $\vec{\mathbf{L}}$ are integer multiples of $\hbar$.

Because the *x* and *y* components of the orbital angular momentum vector are not quantized, the vector $\vec{\mathbf{L}}$ lies on the surface of a cone.

Physical Interpretation of the Quantum Numbers

The Orbital Magnetic Quantum Number m_l



When $\vec{B} = 0$, the excited state has a single energy and only a single spectral line at f_0 is observed.

Atoms in three excited states decay to the ground state with three different energies, and three spectral lines are observed.

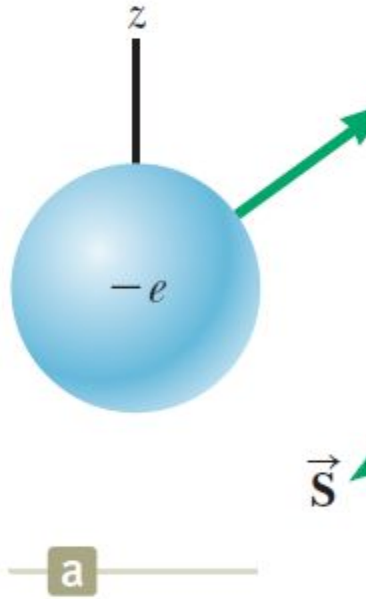
Spectrum without magnetic field

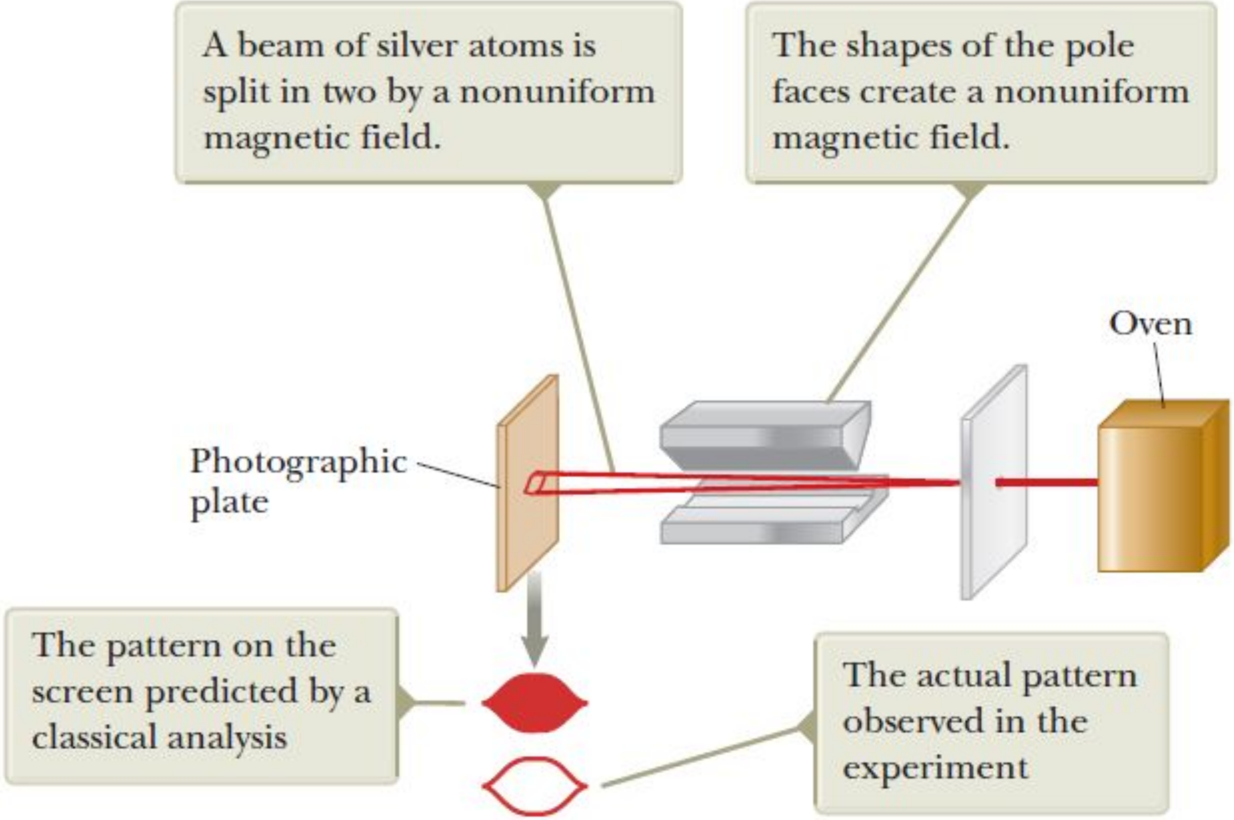
Spectrum with magnetic field present

Physical Interpretation of the Quantum Numbers

The Spin Magnetic Quantum Number m_s

Electron spin




A beam of silver atoms is split in two by a nonuniform magnetic field.

The shapes of the pole faces create a nonuniform magnetic field.

The pattern on the screen predicted by a classical analysis

The actual pattern observed in the experiment

Physical Interpretation of the Quantum Numbers

The Spin Magnetic Quantum Number m_s

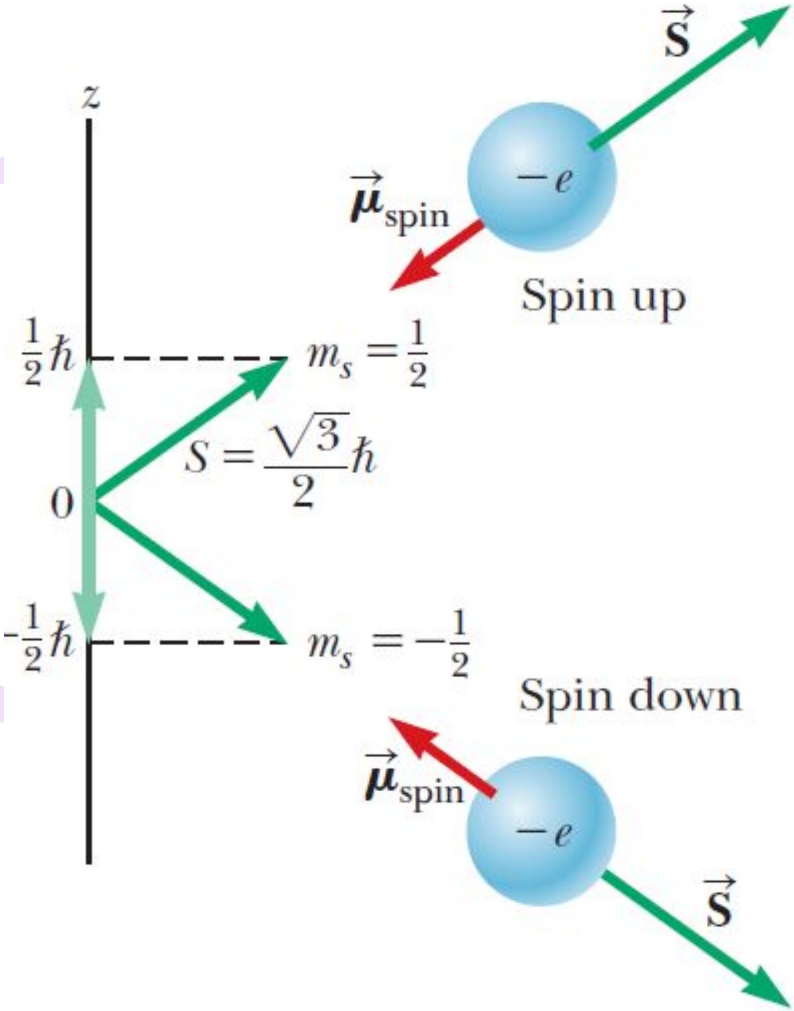
Because spin is a form of angular momentum, it must follow the same quantum rules as orbital angular momentum. The magnitude of the **spin angular momentum** for the electron is

$$S = \sqrt{s(s+1)}\hbar = \frac{\sqrt{3}}{2}\hbar$$

$$S_z = m_s\hbar = \pm\tfrac{1}{2}\hbar$$

Physical Interpretation of the Quantum Numbers

The Spin Magnetic Quantum Number m_s

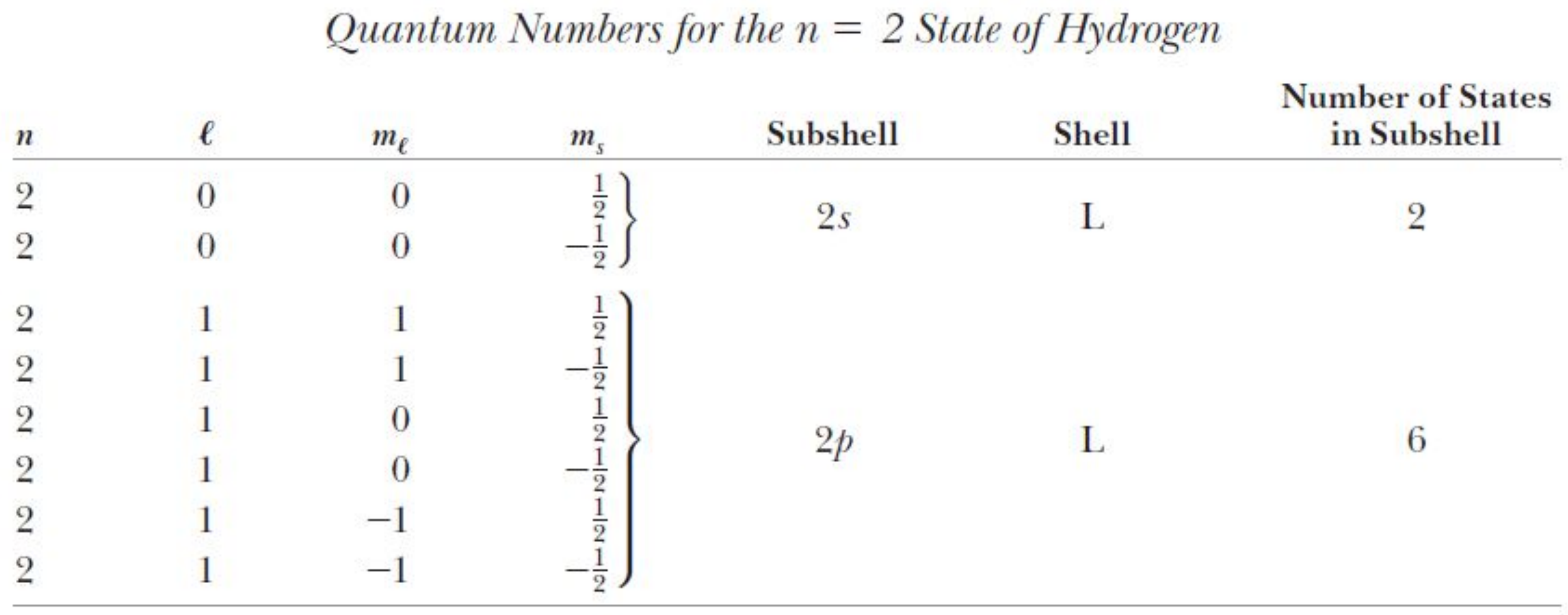


$$\vec{\mu}_{\text{spin}} = -\frac{e}{m_e}\vec{S}$$

$$\vec{\mu}_{\text{spin},z} = \pm\frac{e\hbar}{2m_e}$$

Physical Interpretation of the Quantum Numbers

The Spin Magnetic Quantum Number m_s



Quantum Numbers for the $n = 2$ State of Hydrogen

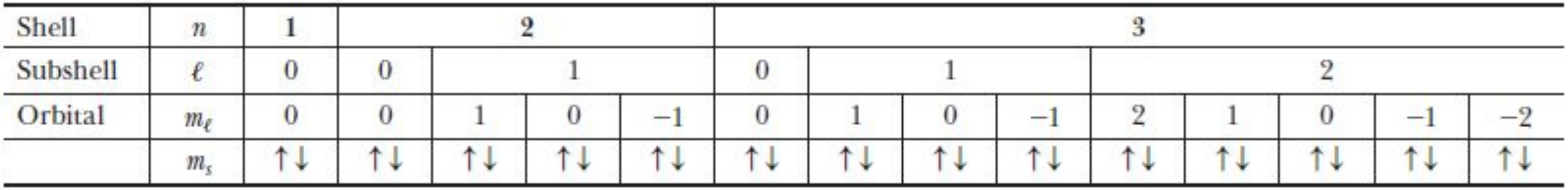
n	ℓ	m_ℓ	m_s	Subshell	Shell	Number of States in Subshell
2	0	0	$\frac{1}{2}$	2*s*	L	2
2	0	0	$-\frac{1}{2}$			
2	1	1	$\frac{1}{2}$	2*p*	L	6
2	1	1	$-\frac{1}{2}$			
2	1	0	$\frac{1}{2}$			
2	1	0	$-\frac{1}{2}$			
2	1	−1	$\frac{1}{2}$			
2	1	−1	$-\frac{1}{2}$			

The Exclusion Principle and the Periodic Table

For our discussion of atoms with many electrons, it is often easiest to assign the quantum numbers to the electrons in the atom as opposed to the entire atom. An obvious question that arises here is, “How many electrons can be in a particular quantum state?” Pauli answered this important question in 1925, in a statement known as the **exclusion principle:**

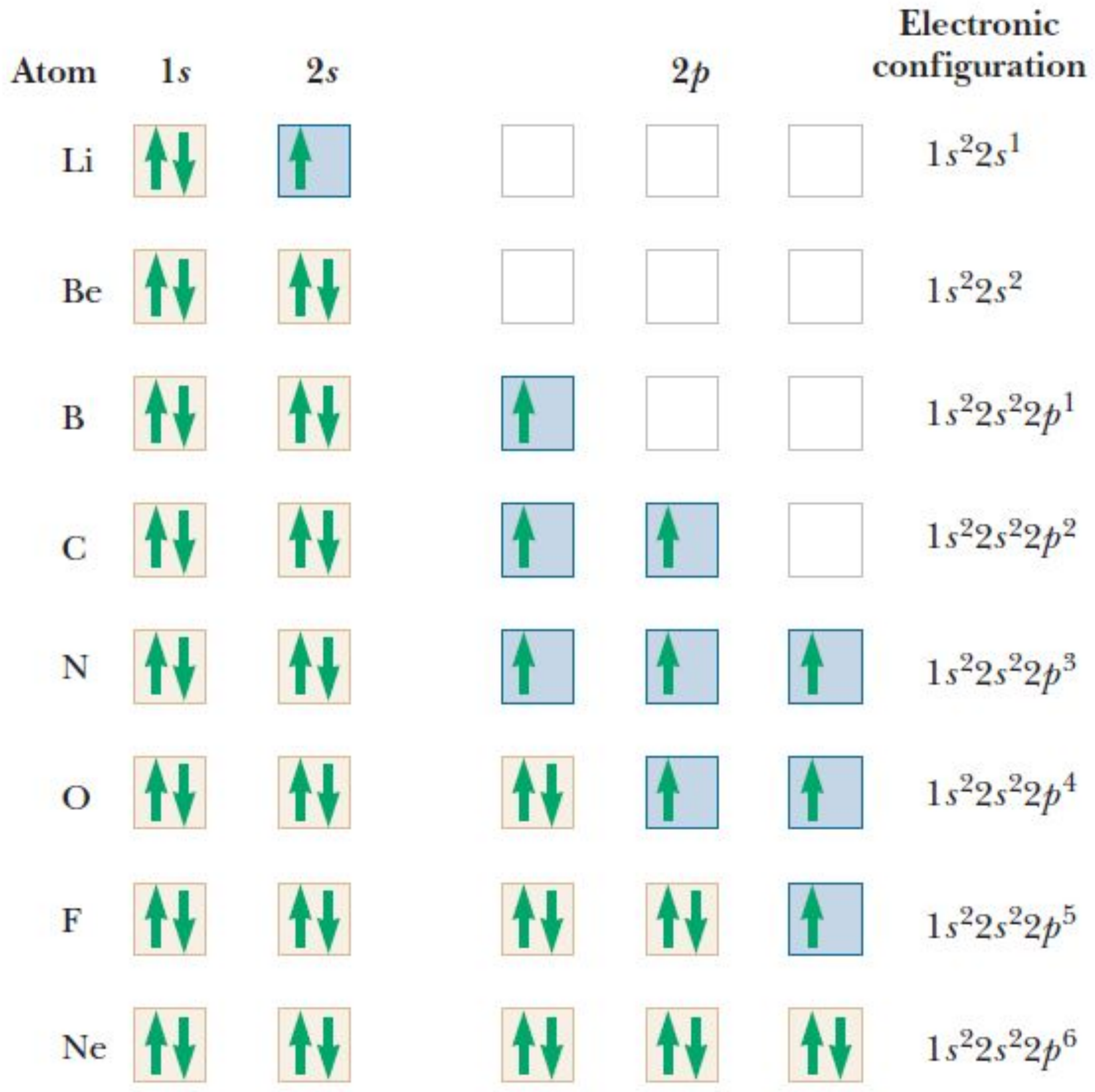
No two electrons can ever be in the same quantum state; therefore, no two electrons in the same atom can have the same set of quantum numbers.

Allowed Quantum States for an Atom Up to $n = 3$



Shell	n	1	2				3								
Subshell	ℓ	0	0	1			0	1			2				
Orbital	m_ℓ	0	0	1	0	−1	0	1	0	−1	2	1	0	−1	−2
	m_s	↑↓	↑↓	↑↓	↑↓	↑↓	↑↓	↑↓	↑↓	↑↓	↑↓	↑↓	↑↓	↑↓	↑↓

The Exclusion Principle and the Periodic



Atom	1s	2s		2p		Electronic configuration
Li	↑↓	↑				$1s^22s^1$
Be	↑↓	↑↓				$1s^22s^2$
B	↑↓	↑↓	↑			$1s^22s^22p^1$
C	↑↓	↑↓	↑	↑		$1s^22s^22p^2$
N	↑↓	↑↓	↑	↑	↑	$1s^22s^22p^3$
O	↑↓	↑↓	↑↓	↑	↑	$1s^22s^22p^4$
F	↑↓	↑↓	↑↓	↑↓	↑	$1s^22s^22p^5$
Ne	↑↓	↑↓	↑↓	↑↓	↑↓	$1s^22s^22p^6$

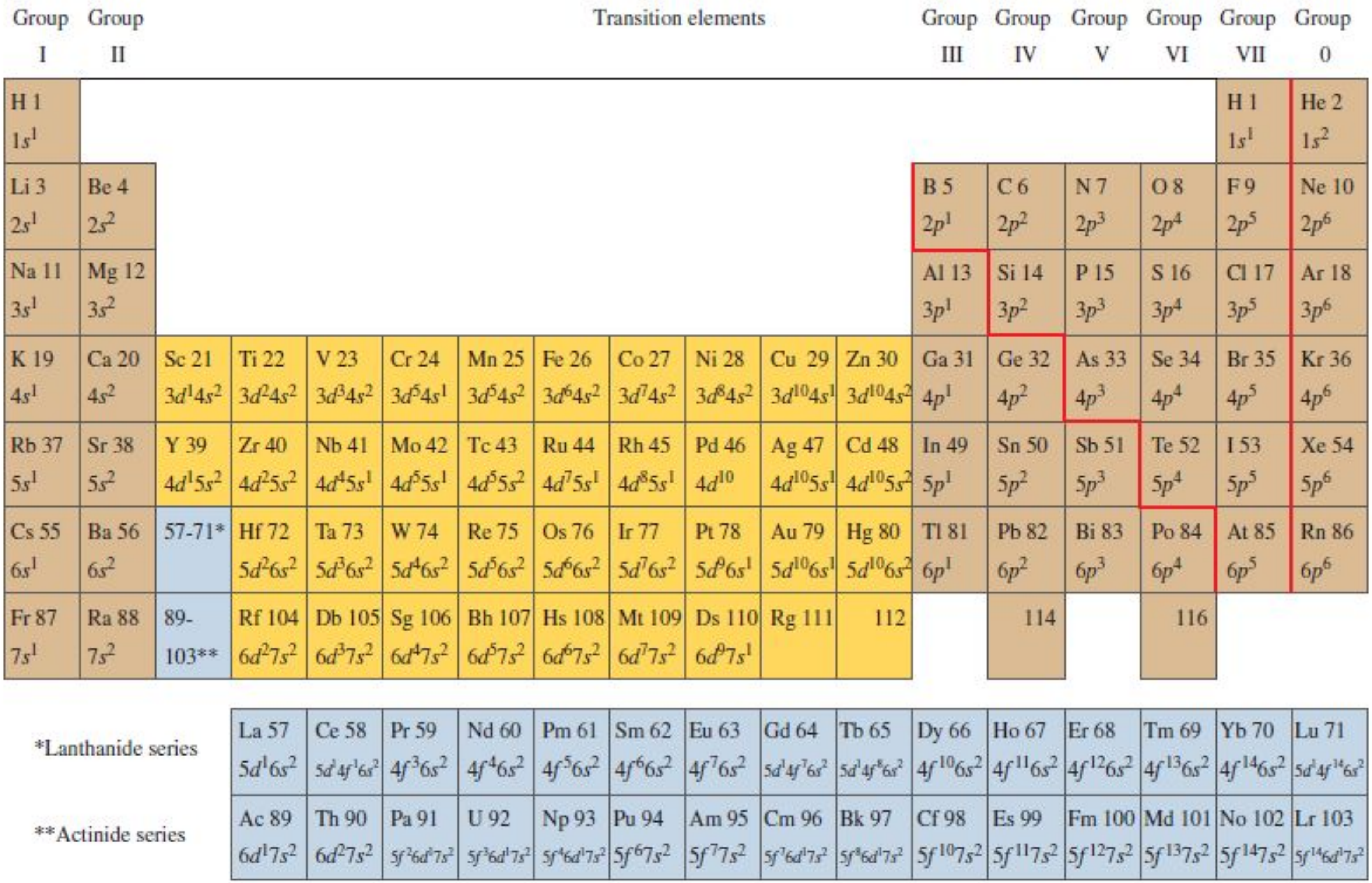
The filling of electronic states must obey both the exclusion principle and Hund’s rule

The Exclusion Principle and the Periodic Table

Hund's rule, states that

when an atom has orbitals of equal energy, the order in which they are filled by electrons is such that a maximum number of electrons have unpaired spins.

The Exclusion Principle and the Periodic

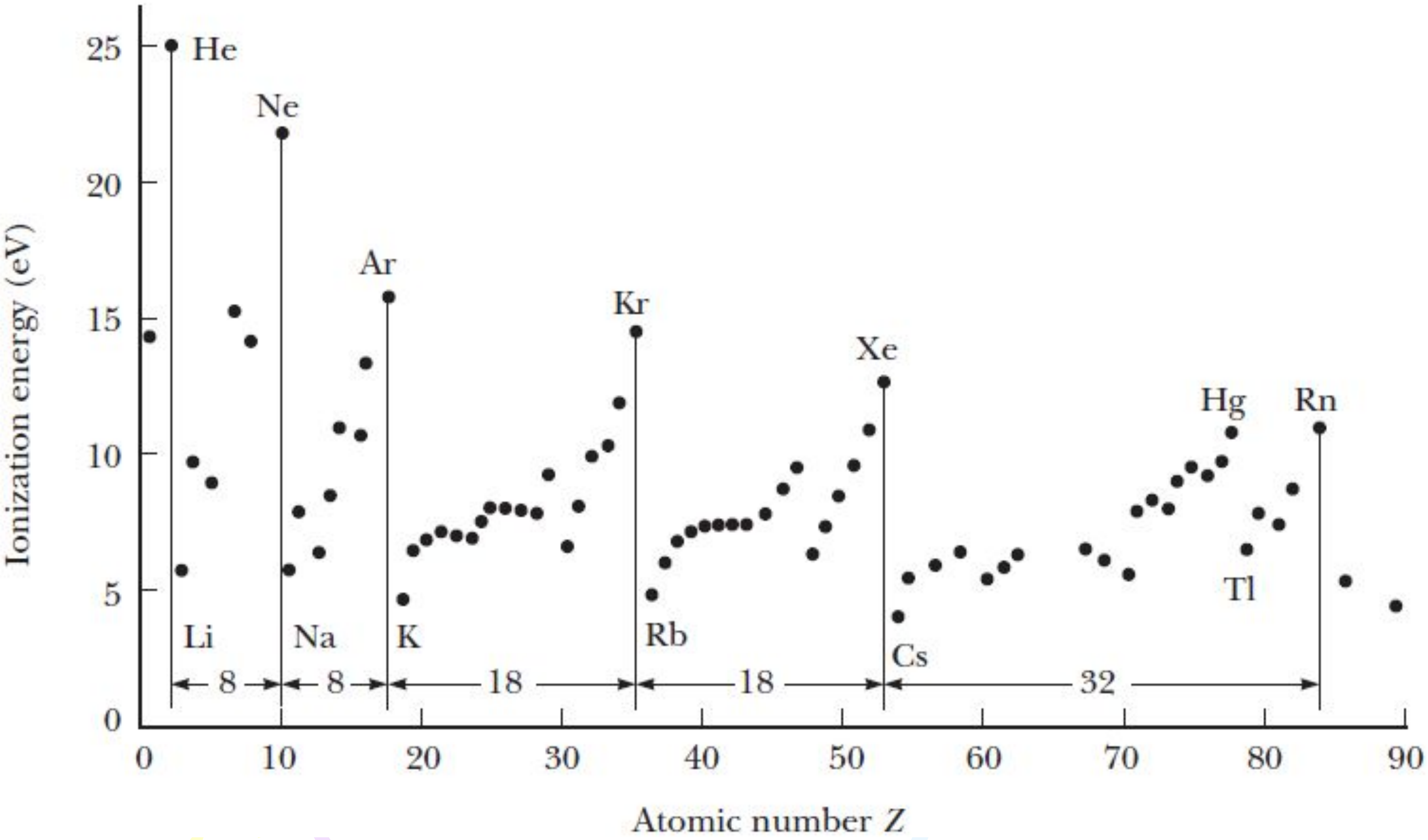


Group I	Group II	Transition elements										Group III	Group IV	Group V	Group VI	Group VII	Group 0
H 1 $1s^1$																H 1 $1s^1$	He 2 $1s^2$
Li 3 $2s^1$	Be 4 $2s^2$											B 5 $2p^1$	C 6 $2p^2$	N 7 $2p^3$	O 8 $2p^4$	F 9 $2p^5$	Ne 10 $2p^6$
Na 11 $3s^1$	Mg 12 $3s^2$											Al 13 $3p^1$	Si 14 $3p^2$	P 15 $3p^3$	S 16 $3p^4$	Cl 17 $3p^5$	Ar 18 $3p^6$
K 19 $4s^1$	Ca 20 $4s^2$	Sc 21 $3d^1 4s^2$	Ti 22 $3d^2 4s^2$	V 23 $3d^3 4s^2$	Cr 24 $3d^5 4s^1$	Mn 25 $3d^5 4s^2$	Fe 26 $3d^6 4s^2$	Co 27 $3d^7 4s^2$	Ni 28 $3d^8 4s^2$	Cu 29 $3d^{10} 4s^1$	Zn 30 $3d^{10} 4s^2$	Ga 31 $4p^1$	Ge 32 $4p^2$	As 33 $4p^3$	Se 34 $4p^4$	Br 35 $4p^5$	Kr 36 $4p^6$
Rb 37 $5s^1$	Sr 38 $5s^2$	Y 39 $4d^1 5s^2$	Zr 40 $4d^2 5s^2$	Nb 41 $4d^4 5s^1$	Mo 42 $4d^5 5s^1$	Tc 43 $4d^5 5s^2$	Ru 44 $4d^7 5s^1$	Rh 45 $4d^8 5s^1$	Pd 46 $4d^{10}$	Ag 47 $4d^{10} 5s^1$	Cd 48 $4d^{10} 5s^2$	In 49 $5p^1$	Sn 50 $5p^2$	Sb 51 $5p^3$	Te 52 $5p^4$	I 53 $5p^5$	Xe 54 $5p^6$
Cs 55 $6s^1$	Ba 56 $6s^2$	57-71*	Hf 72 $5d^2 6s^2$	Ta 73 $5d^3 6s^2$	W 74 $5d^4 6s^2$	Re 75 $5d^5 6s^2$	Os 76 $5d^6 6s^2$	Ir 77 $5d^7 6s^2$	Pt 78 $5d^9 6s^1$	Au 79 $5d^{10} 6s^1$	Hg 80 $5d^{10} 6s^2$	Tl 81 $6p^1$	Pb 82 $6p^2$	Bi 83 $6p^3$	Po 84 $6p^4$	At 85 $6p^5$	Rn 86 $6p^6$
Fr 87 $7s^1$	Ra 88 $7s^2$	89-103**	Rf 104 $6d^2 7s^2$	Db 105 $6d^3 7s^2$	Sg 106 $6d^4 7s^2$	Bh 107 $6d^5 7s^2$	Hs 108 $6d^6 7s^2$	Mt 109 $6d^7 7s^2$	Ds 110 $6d^9 7s^1$	Rg 111	112		114		116		

*Lanthanide series	La 57 $5d^1 6s^2$	Ce 58 $5d^1 4f^1 6s^2$	Pr 59 $4f^3 6s^2$	Nd 60 $4f^4 6s^2$	Pm 61 $4f^5 6s^2$	Sm 62 $4f^6 6s^2$	Eu 63 $4f^7 6s^2$	Gd 64 $5d^1 4f^7 6s^2$	Tb 65 $5d^1 4f^8 6s^2$	Dy 66 $4f^{10} 6s^2$	Ho 67 $4f^{11} 6s^2$	Er 68 $4f^{12} 6s^2$	Tm 69 $4f^{13} 6s^2$	Yb 70 $4f^{14} 6s^2$	Lu 71 $5d^1 4f^{14} 6s^2$
**Actinide series	Ac 89 $6d^1 7s^2$	Th 90 $6d^2 7s^2$	Pa 91 $5f^2 6d^1 7s^2$	U 92 $5f^3 6d^1 7s^2$	Np 93 $5f^4 6d^1 7s^2$	Pu 94 $5f^6 7s^2$	Am 95 $5f^7 7s^2$	Cm 96 $5f^7 6d^1 7s^2$	Bk 97 $5f^8 6d^1 7s^2$	Cf 98 $5f^{10} 7s^2$	Es 99 $5f^{11} 7s^2$	Fm 100 $5f^{12} 7s^2$	Md 101 $5f^{13} 7s^2$	No 102 $5f^{14} 7s^2$	Lr 103 $5f^{14} 6d^1 7s^2$

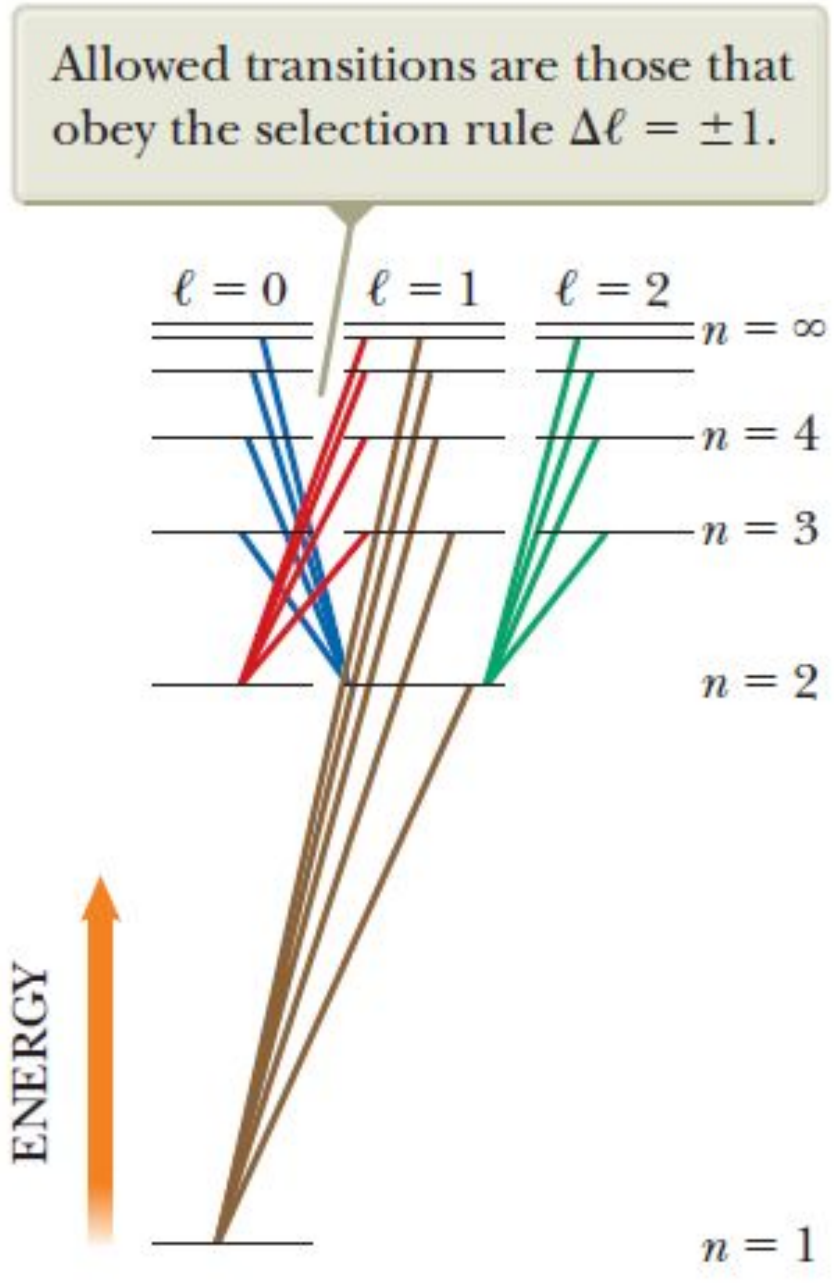
The periodic table

The Exclusion Principle and the Periodic



Ionization energy of the elements versus atomic number

More on Atomic Spectra: Visible and X-Ray



Transitions for which *l* does not change are very unlikely to occur and are called *forbidden transitions*. (Such transitions actually can occur, but their probability is very low relative to the probability of "allowed" transitions.) The various diagonal lines represent allowed transitions between stationary states. Whenever an atom makes a transition from a higher energy state to a lower one, a photon of light is emitted.

More on Atomic Spectra: Visible and X-Ray

The **selection rules** for the *allowed transitions are*

$$\Delta\ell = \pm 1 \quad \text{and} \quad \Delta m_\ell = 0, \pm 1$$

the allowed energies for one-electron atoms and ions, such as hydrogen and He$^+$ are

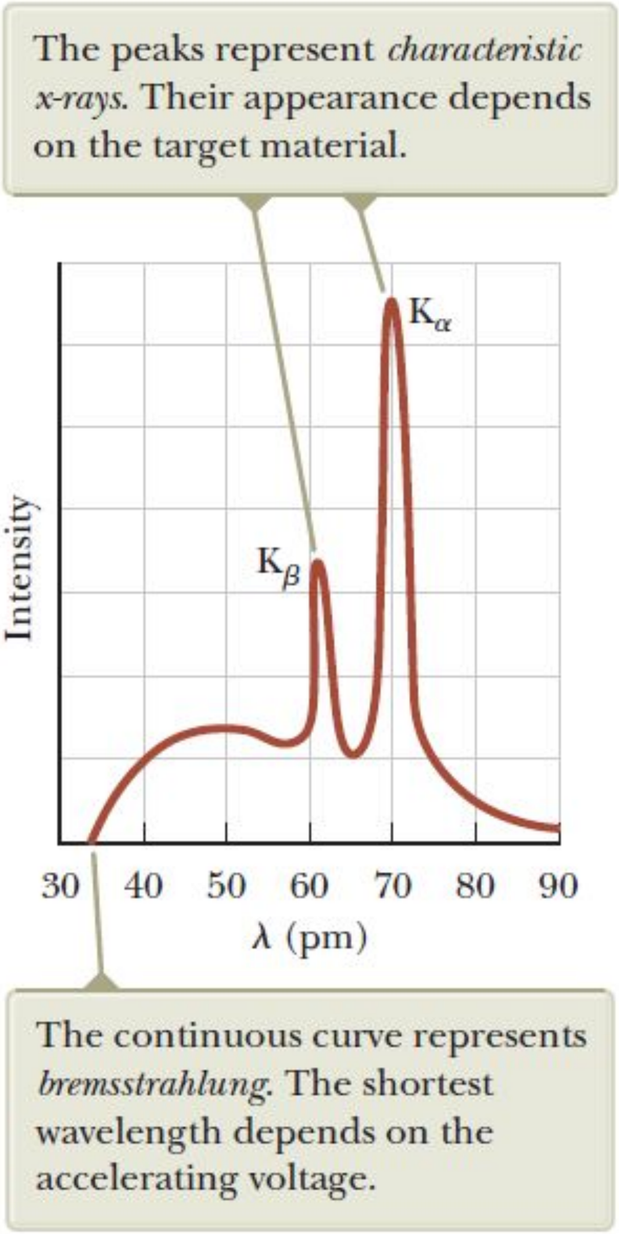
$$E_n = -\frac{k_e e^2}{2a_0}\left(\frac{Z^2}{n^2}\right) = -\frac{(13.6\ \text{eV})Z^2}{n^2}$$

This equation was developed from the Bohr theory, but it serves as a good first approximation in quantum theory as well.

$$E_n = -\frac{(13.6\ \text{eV})Z_{\text{eff}}^2}{n^2}$$

More on Atomic Spectra: Visible and X-Ray

X-Ray Spectra



The peaks represent *characteristic x-rays.* Their appearance depends on the target material.

The continuous curve represents *bremsstrahlung.* The shortest wavelength depends on the accelerating voltage.

X-rays are emitted when high-energy electrons or any other charged particles bombard a metal target. The x-ray spectrum typically consists of a broad continuous band containing a series of sharp lines.

X-ray radiation with its origin in the slowing down of electrons is called **bremsstrahlung,** the German word for "braking radiation."

The discrete lines called **characteristic x-rays.**

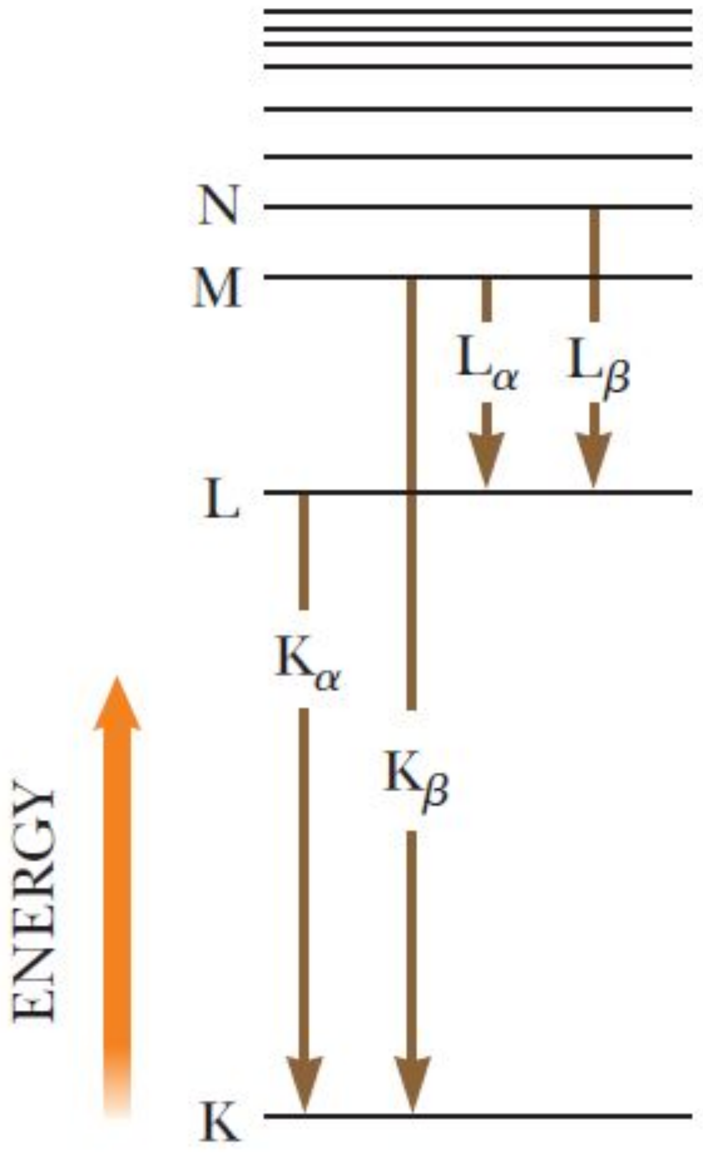
More on Atomic Spectra: Visible and X-Ray

X-Ray Spectra

Figure shows a machine that uses a linear accelerator to accelerate electrons up to 18 MeV and smash them into a tungsten target. The result is a beam of photons, up to a maximum energy of 18 MeV, which is actually in the gamma-ray range. This radiation is directed at the tumor in the patient.

More on Atomic Spectra: Visible and X-Ray

X-Ray Spectra



Other characteristic x-ray lines are formed when electrons drop from upper levels to vacancies other than those in the K shell. For example, L lines are produced when vacancies in the L shell are filled by electrons dropping from higher shells. An L_α line is produced as an electron drops from the M shell to the L shell, and an L_β line is produced by a transition from the N shell to the L shell.

More on Atomic Spectra: Visible and X-Ray

X-Ray Spectra

We can now estimate the energy associated with an electron in the L shell:

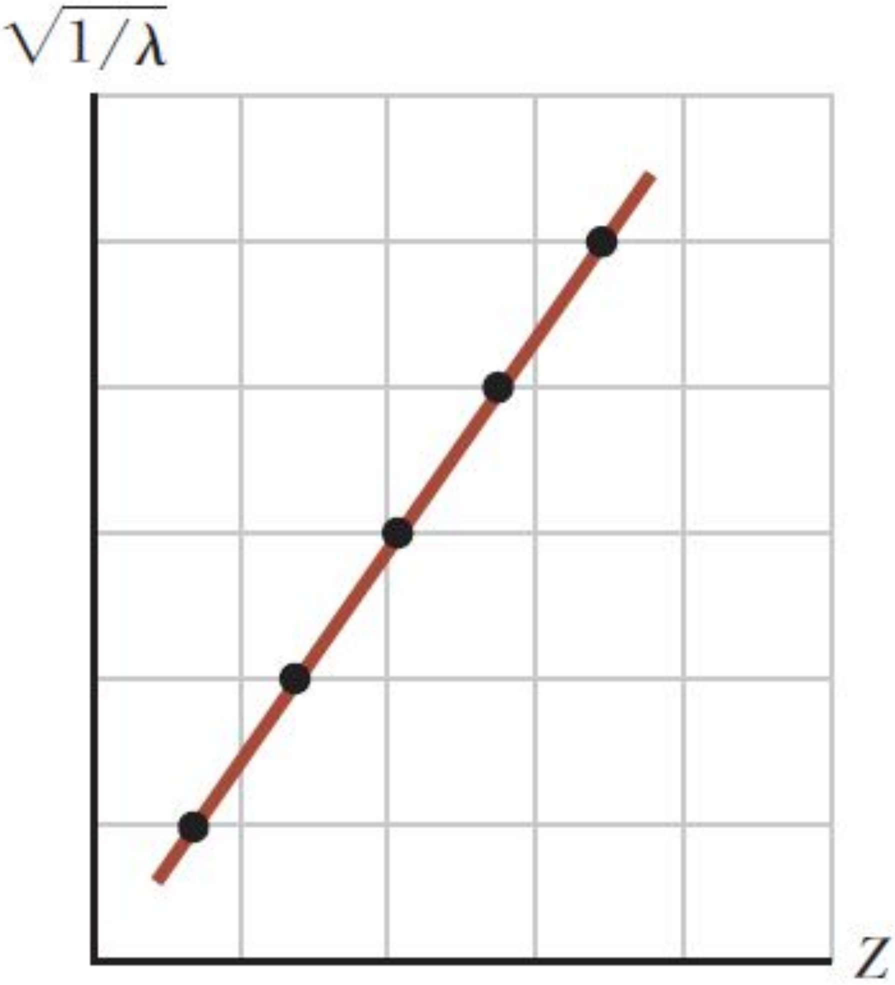
$$E_L = -(Z-1)^2 \frac{13.6\text{ eV}}{2^2}$$

After the atom makes the transition, there are two electrons in the K shell. We can approximate the energy associated with one of these electrons as that of a one-electron atom. (In reality, the nuclear charge is reduced somewhat by the negative charge of the other electron, but let's ignore this effect.) Therefore,

$$E_K \approx -Z^2(13.6\text{ eV})$$

More on Atomic Spectra: Visible and X-Ray

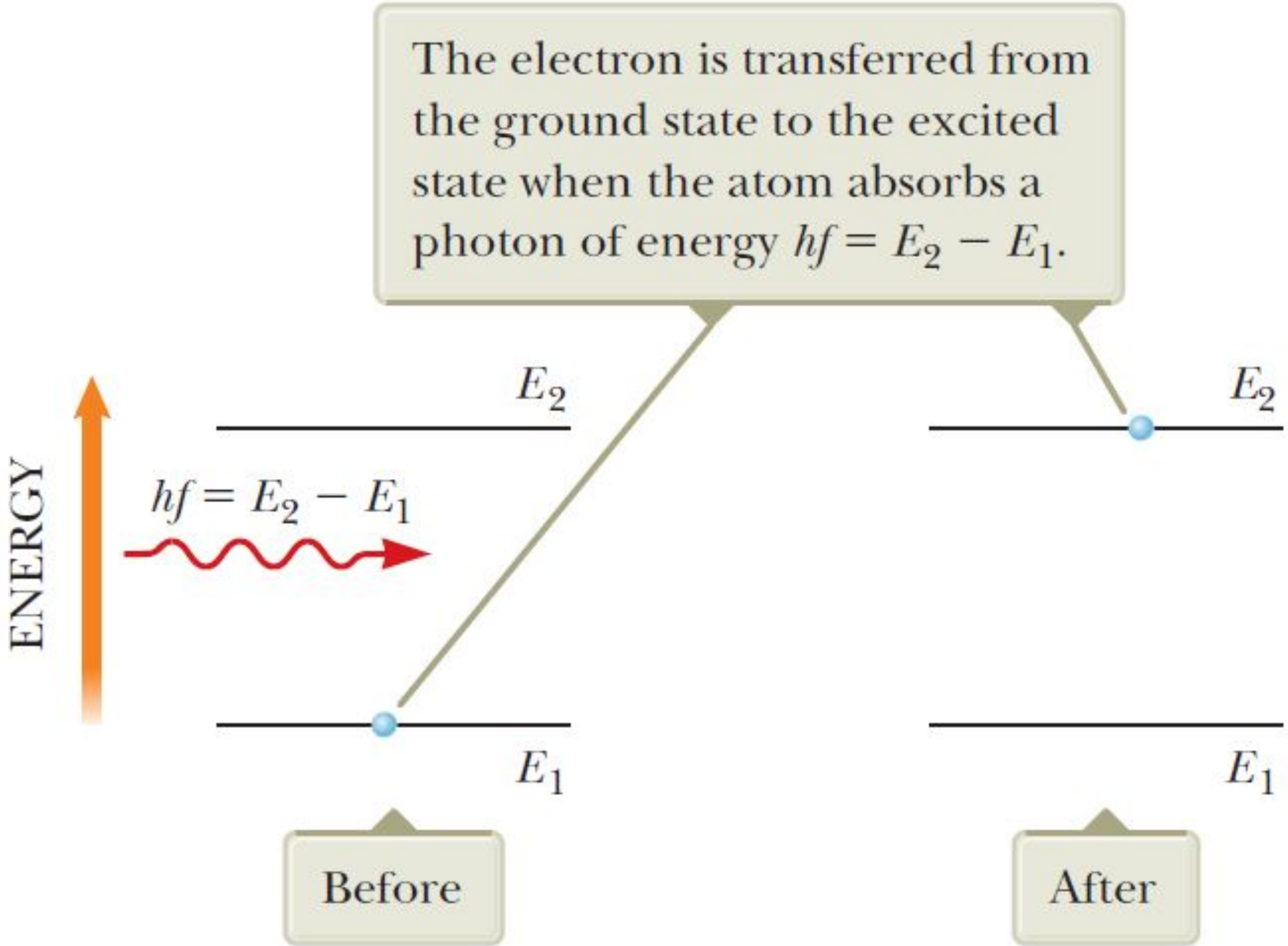
X-Ray Spectra



A Moseley plot of $\sqrt{1/\lambda}$ versus Z, where λ is the wavelength of the Kα x-ray line of the element of atomic number Z.

From this plot, Moseley determined the Z values of elements that had not yet been discovered and produced a periodic table in excellent agreement with the known chemical properties of the elements. Until that experiment, atomic numbers had been merely placeholders for the elements that appeared in the periodic table, the elements being ordered according to mass.

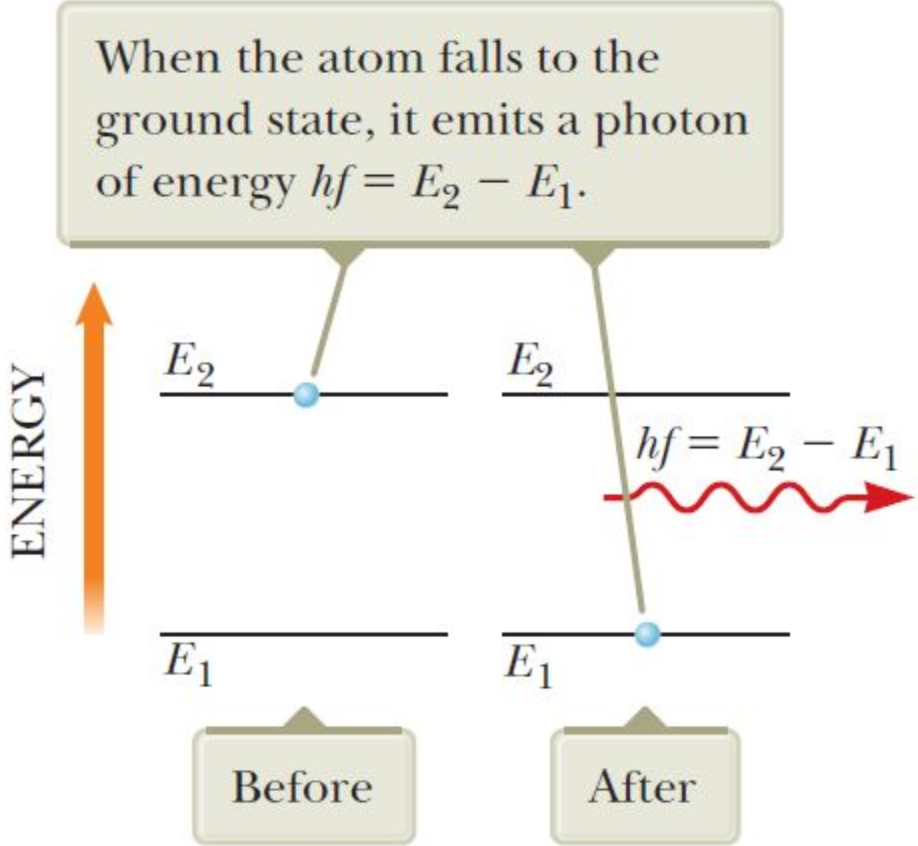
Spontaneous and Stimulated Transitions



The electron is transferred from the ground state to the excited state when the atom absorbs a photon of energy $hf = E_2 - E_1$.

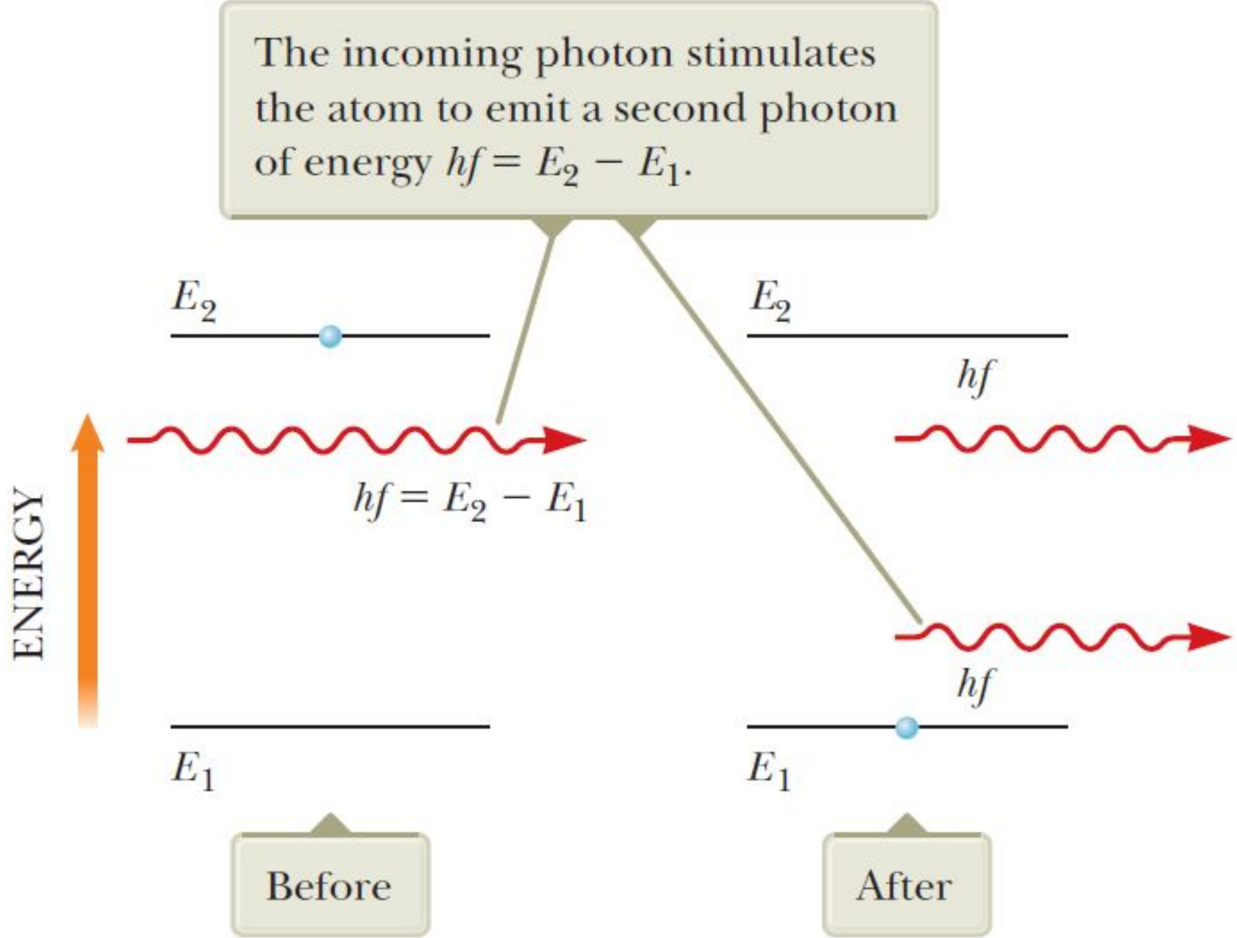
This process is called **stimulated absorption** because the photon stimulates the atom to make the upward transition.

Spontaneous and Stimulated Transitions



Once an atom is in an excited state, the excited atom can make a transition back to a lower energy level, emitting a photon in the process. This process is known as **spontaneous emission** because it happens naturally, without requiring an event to trigger the transition. Typically, an atom remains in an excited state for only about 10^{-8} s.

Spontaneous and Stimulated Transitions



The incoming photon stimulates the atom to emit a second photon of energy $hf = E_2 - E_1$.

In addition to spontaneous emission, **stimulated emission occurs.** In this process, the incident photon is not absorbed; therefore, after the stimulated emission, two photons with identical energy exist: the incident photon and the emitted photon.

Lasers

The primary properties of laser light that make it useful in these technological applications are the following:

• Laser light is coherent. The individual rays of light in a laser beam maintain a fixed phase relationship with one another.
• Laser light is monochromatic. Light in a laser beam has a very narrow range of wavelengths.
• Laser light has a small angle of divergence. The beam spreads out very little, even over large distances.

Lasers

We have described how an incident photon can cause atomic energy transitions either upward (stimulated absorption) or downward (stimulated emission). The two processes are equally probable. When light is incident on a collection of atoms, a net absorption of energy usually occurs because when the system is in thermal equilibrium, many more atoms are in the ground state than in excited states. If the situation can be inverted so that more atoms are in an excited state than in the ground state, however, a net emission of photons can result. Such a condition is called **population inversion.** Population inversion is, in fact, the fundamental principle involved in the operation of a **laser** (an acronym for *l*ight *a*mplification by *s*timulated *e*mission of *r*adiation). The full name indicates one of the requirements for laser light: to achieve laser action, the process of stimulated emission must occur.

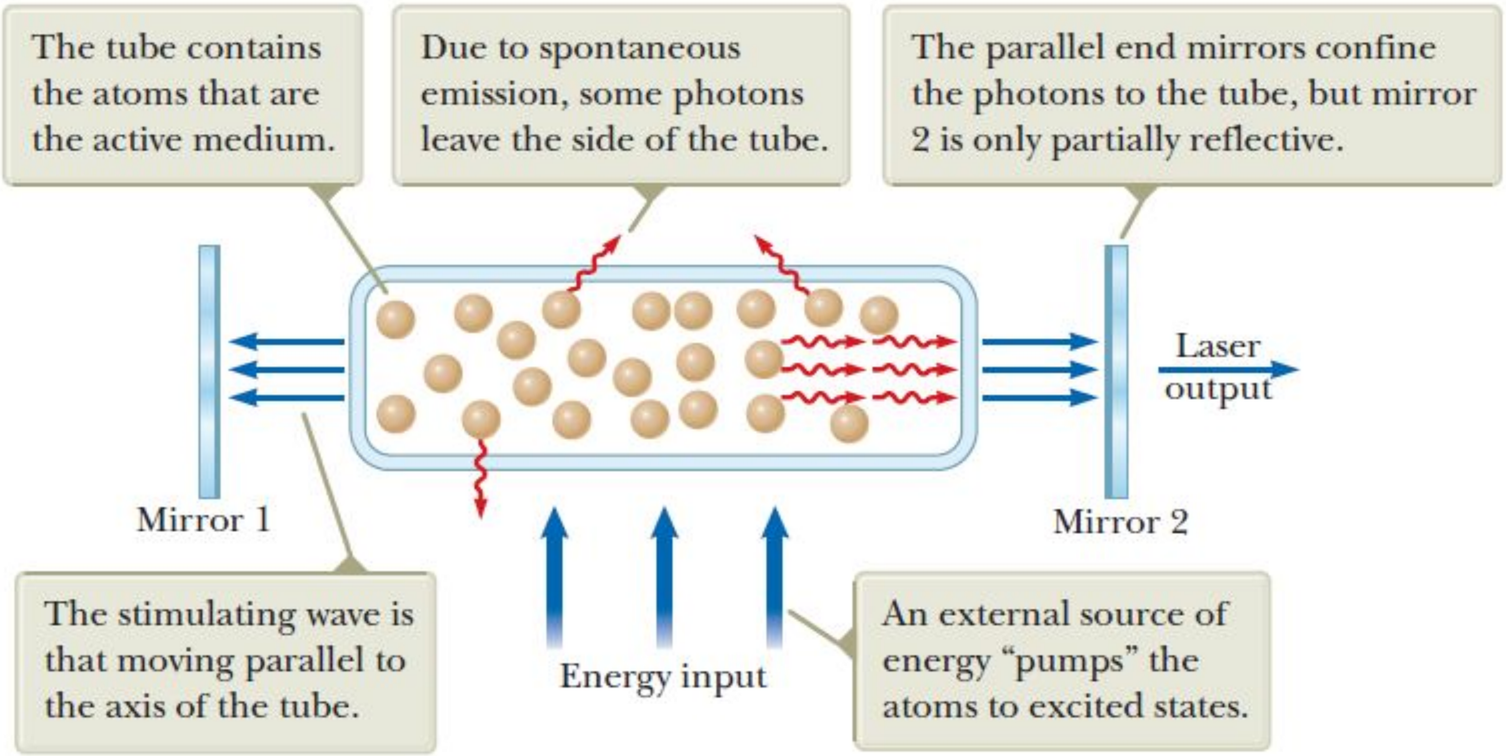
Lasers

For the stimulated emission to result in laser light, there must be a buildup of photons in the system. The following three conditions must be satisfied to achieve this buildup:

- The system must be in a state of population inversion: there must be more atoms in an excited state than in the ground state. That must be true because the number of photons emitted must be greater than the number absorbed.
- The excited state of the system must be a *metastable state,* meaning that its lifetime must be long compared with the usually short lifetimes of excited states, which are typically 1028 s. In this case, the population inversion can be established and stimulated emission is likely to occur before spontaneous emission.

Lasers

- The emitted photons must be confined in the system long enough to enable them to stimulate further emission from other excited atoms. That is achieved by using reflecting mirrors at the ends of the system. One end is made totally reflecting, and the other is partially reflecting. A fraction of the light intensity passes through the partially reflecting end, forming the beam of laser light.



The tube contains the atoms that are the active medium.

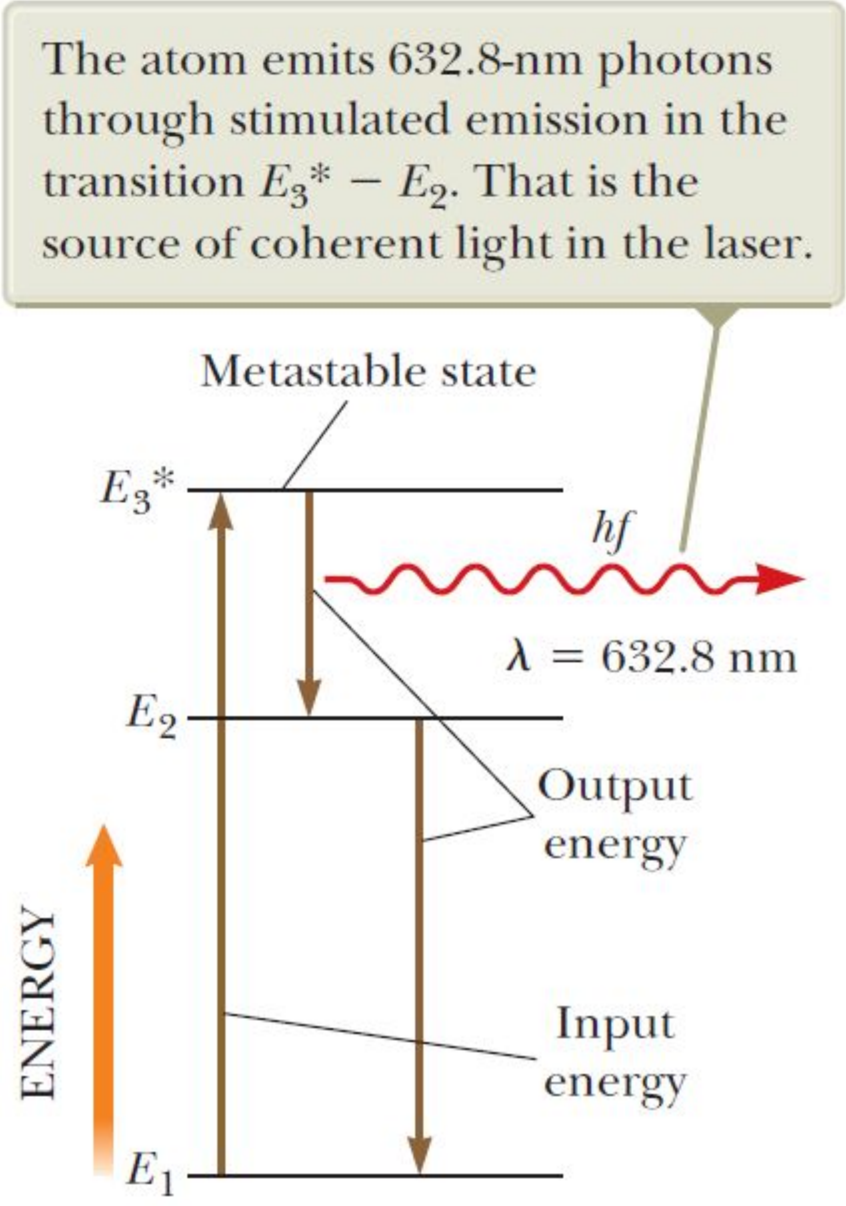
Due to spontaneous emission, some photons leave the side of the tube.

The parallel end mirrors confine the photons to the tube, but mirror 2 is only partially reflective.

The stimulating wave is that moving parallel to the axis of the tube.

An external source of energy “pumps” the atoms to excited states.

Lasers



The atom emits 632.8-nm photons through stimulated emission in the transition $E_3^* - E_2$. That is the source of coherent light in the laser.

One device that exhibits stimulated emission of radiation is the helium–neon gas laser. Figure is an energy-level diagram for the neon atom in this system. The mixture of helium and neon is confined to a glass tube that is sealed at the ends by mirrors. A voltage applied across the tube causes electrons to sweep through the tube, colliding with the atoms of the gases and raising them into excited states. Neon atoms are excited to state E_3^* through this process (the asterisk indicates a metastable state) and also as a result of collisions with excited helium atoms. Stimulated emission occurs, causing neon atoms to make transitions to state E_2. Neighboring excited atoms are also stimulated. The result is the production of coherent light at a wavelength of 632.8 nm.

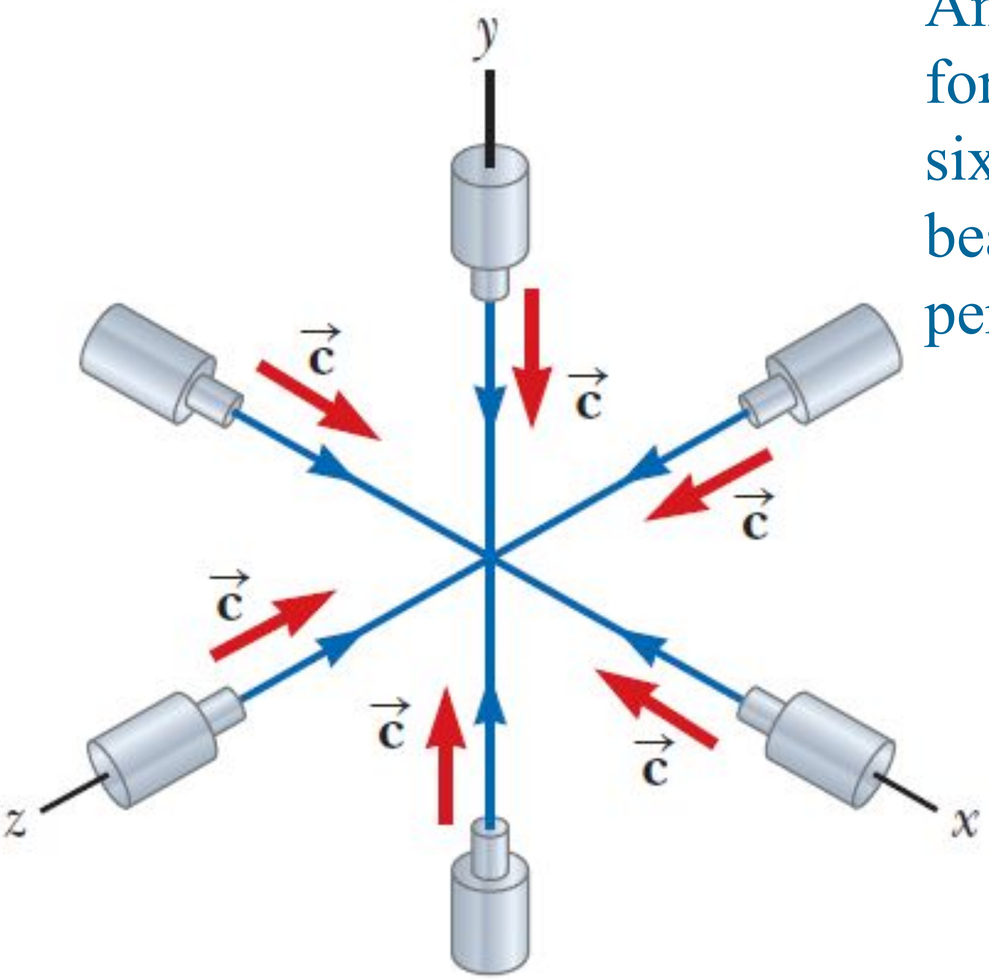
Lasers

Applications

This robot carrying laser scissors, which can cut up to 50 layers of fabric at a time, is one of the many applications of laser technology.

Lasers

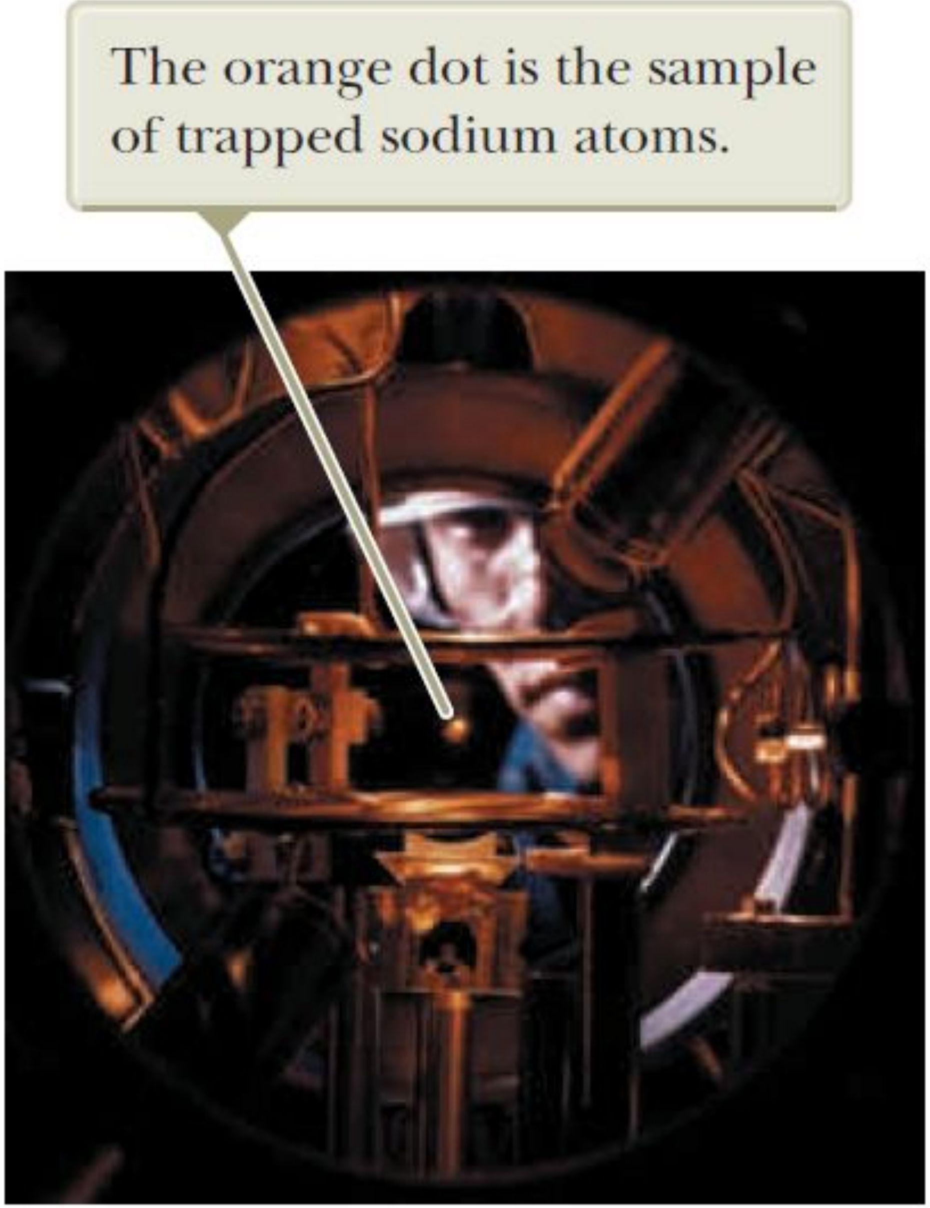
Applications



An optical trap for atoms is formed at the intersection point of six counterpropagating laser beams along mutually perpendicular axes.

Lasers

Applications


The orange dot is the sample of trapped sodium atoms.

An extension of laser trapping, *laser cooling,* is possible because the normal high speeds of the atoms are reduced when they are restricted to the region of the trap. As a result, the temperature of the collection of atoms can be reduced to a few microkelvins. The technique of laser cooling allows scientists to study the behavior of atoms at extremely low temperatures