Atoms

- Quantum physics explains the energy levels of atoms with enormous accuracy. This is possible, since these levels have long lifetime (uncertainty relation for $\Delta E, \Delta t$).

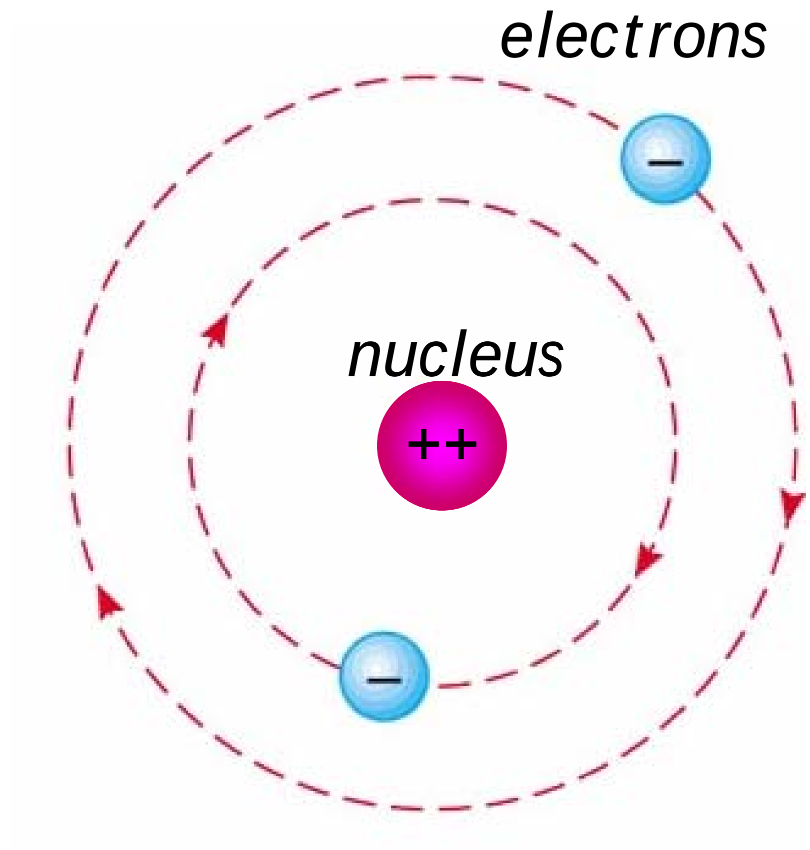
- Radiation from atoms and molecules enables the most accurate time and length measurements: Atomic clocks

- Quantum physics explains why atoms are stable. The planetary model of atoms plus Maxwell's equations of electromagnetism would predict that orbiting electrons act like an antenna and radiate their energy away.

Ch. 13.6, 13.7

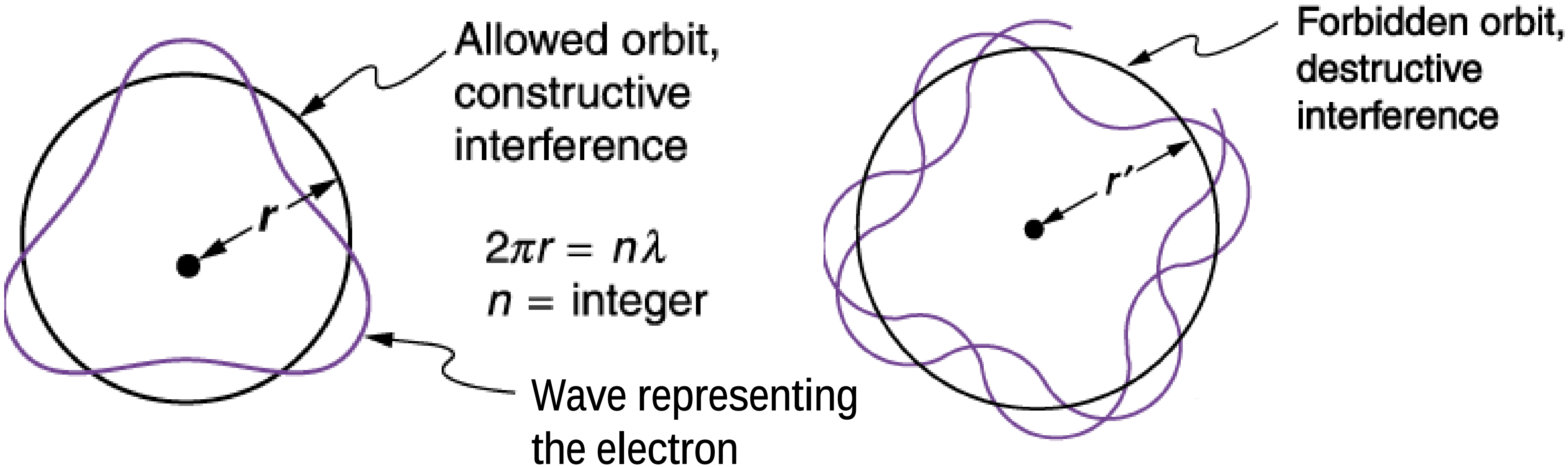
Classical planetary model of an atom

- Positive charge is concentrated at the nucleus.
- Electrons orbit the nucleus, like planets orbit the Sun.
- Coulomb's law of electric attraction is analogous to Newton's law of gravitation.
- The simplest atom is hydrogen, consisting of a proton and an electron.



Helium atom

Early quantum model of an atom



Louis deBoglie Niels Bohr

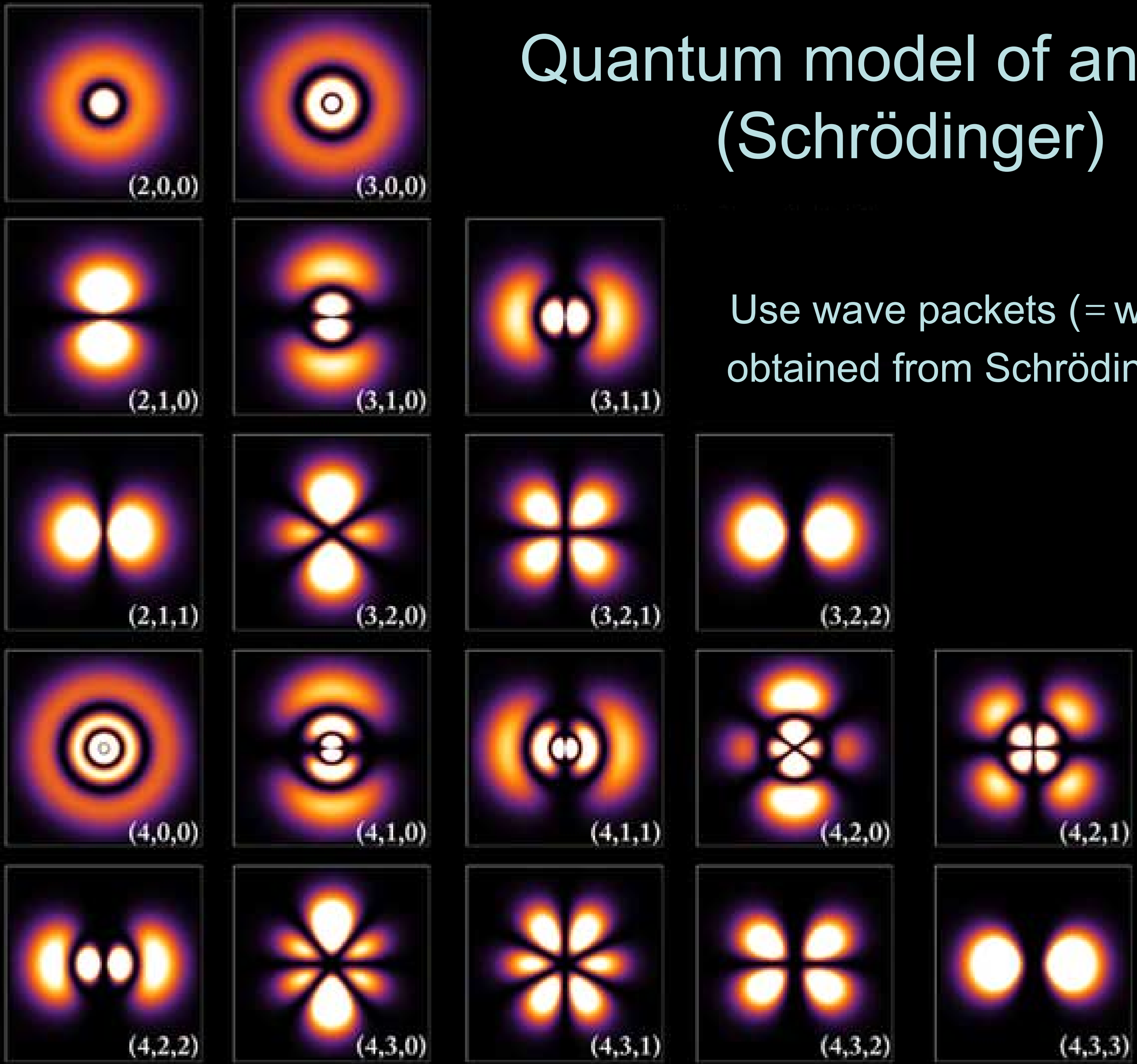
The electron oscillates around its classical orbit.

Need an integer number of oscillations per orbit.

That leads to discrete frequencies, i.e., discrete energy levels according to Planck.

The lowest level is stable simply because there is no lower level available to the electron.

Quantum model of an atom (Schrödinger)



Use wave packets (= wave functions), obtained from Schrödinger's equation.

Quantum numbers: (n, l, m_l)

Quantum numbers of the H atom

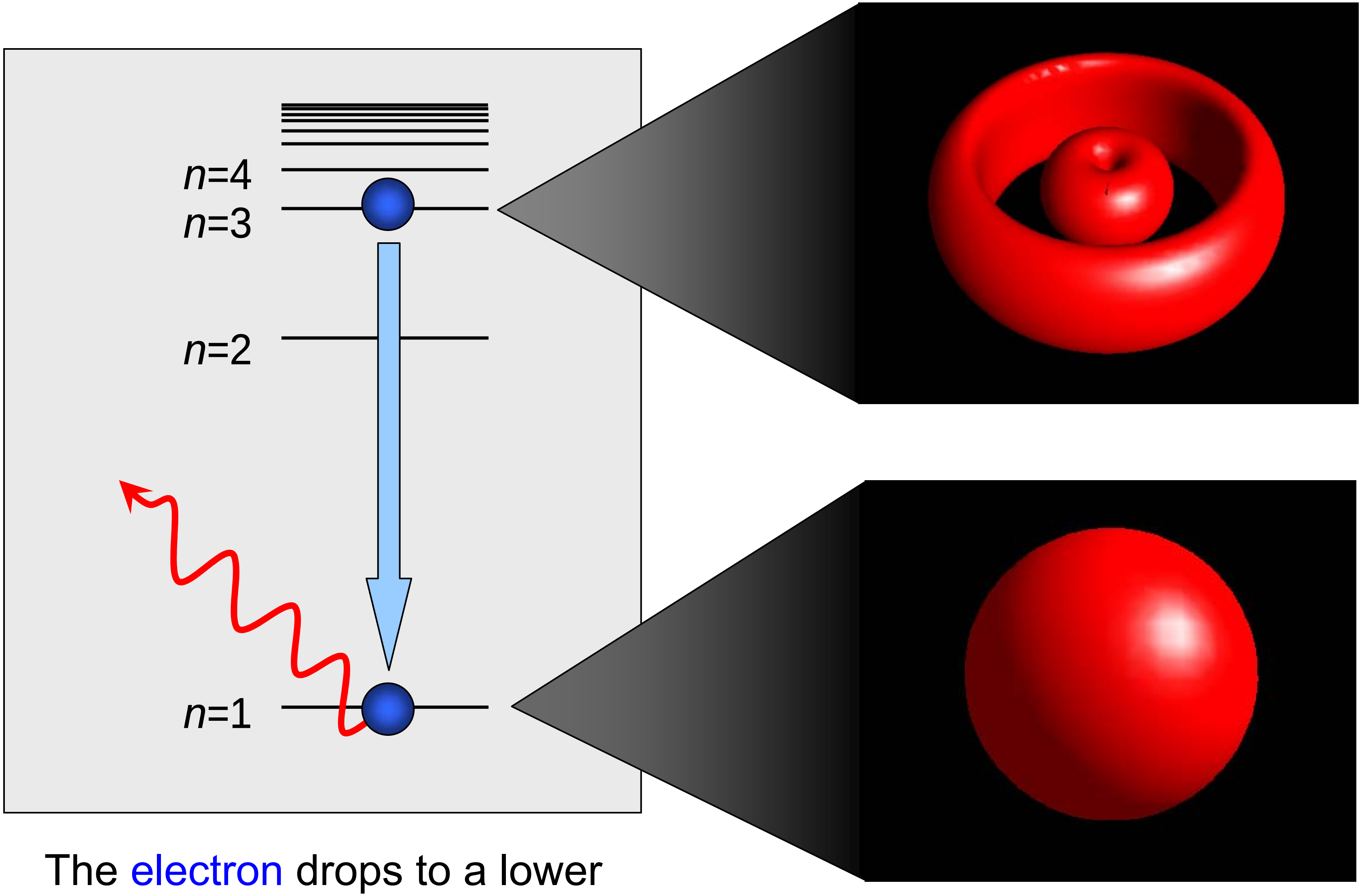
- The quantum state of the H atom is characterized by a set of four quantum numbers: E, n , l , m_l
- These four quantum numbers are related to the four coordinates of space-time:

  E is related to time by the uncertainty relation.

  n is related to the radial coordinate in space.

  l , m_l are related to the angular coordinates in space.

Quantum description of radiation



The electron drops to a lower level, emitting a photon.

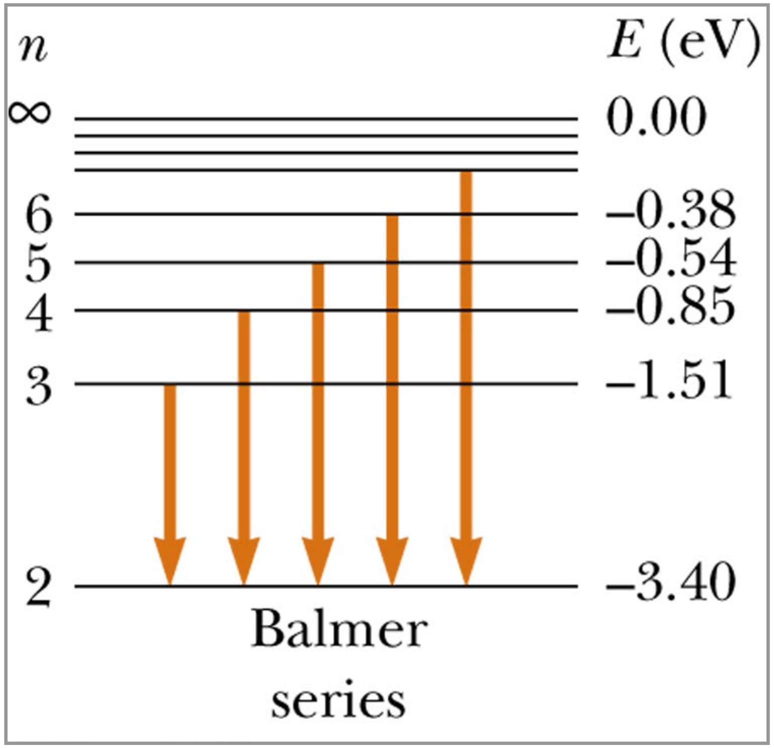
Electron wave packets for n=1,3

Calculating the energy of the emitted photons

- Example: Transitions to n=2.
- The energy levels are given by:

$$\boxed{E_n = -Ry / n^2}$$

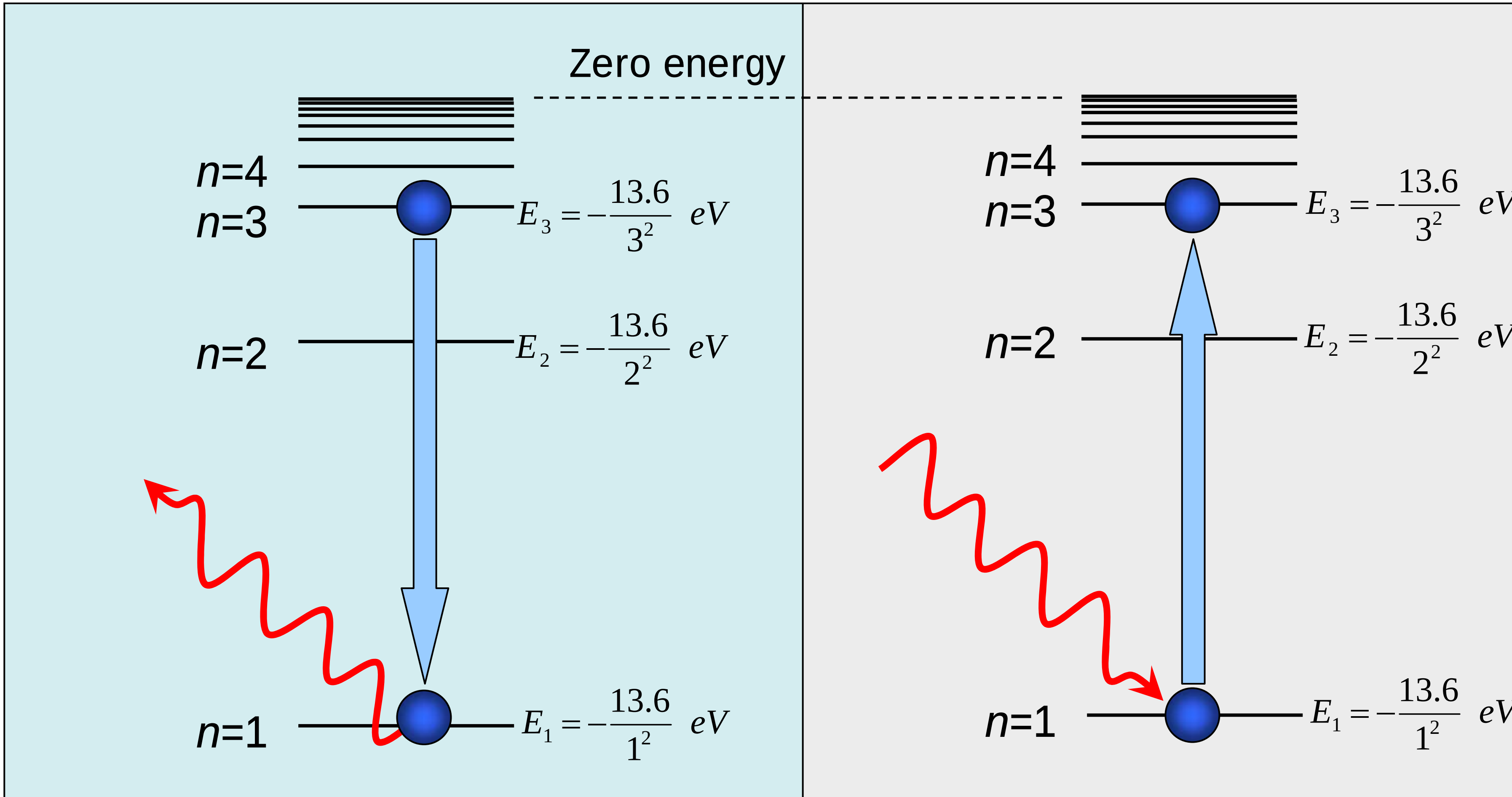
- Ry = 13.6 eV = Rydberg constant.



- The difference between the electron energy levels is the photon energy. For $3 \Rightarrow 2$:

$$E_{photon} = \left(\left(-\frac{13.6}{3^2} \right) - \left(-\frac{13.6}{2^2} \right) \right) = 1.89 \ eV$$

Emission and absorption of a photon

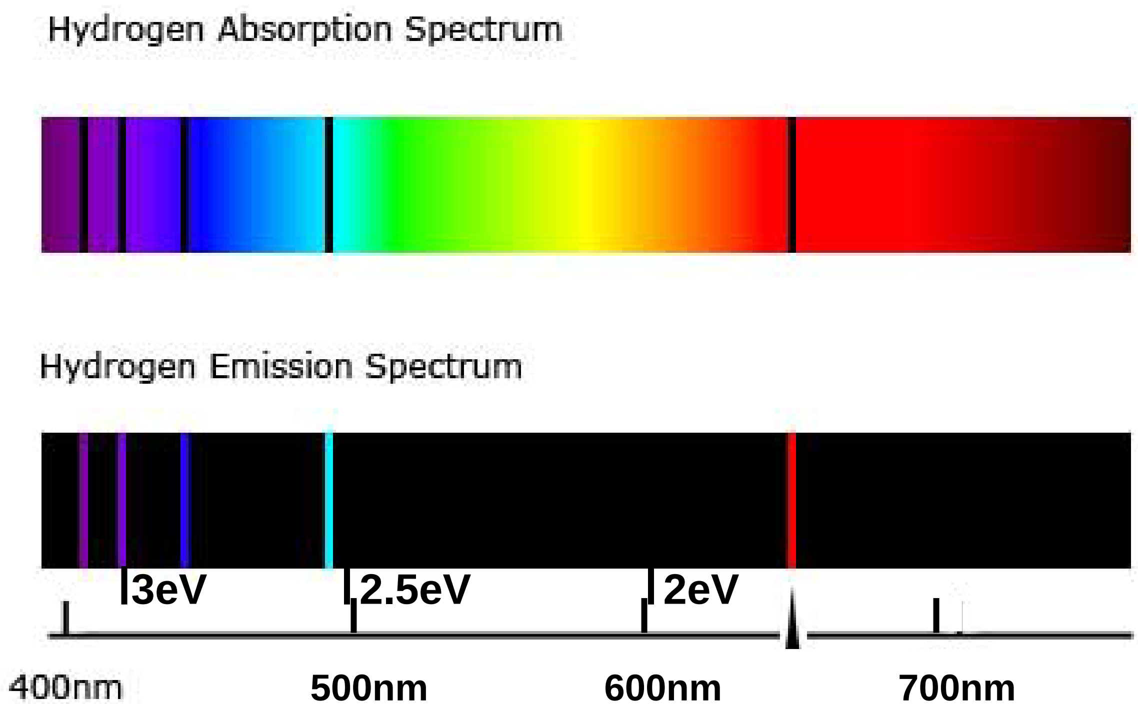


A photon is emitted when an electron drops from a higher to a lower energy level.

A photon with the right energy causes an electron to jump to an upper energy level.

The hydrogen spectrum

- The transitions to the n=1 level are in the ultraviolet.
- The transitions to the n=2 level are in the visible.
- The strong transition from n=3 to n=2 makes hydrogen glow red. This red glow is observed frequently, because hydrogen makes up ¾ of the visible universe (helium ¼).



Red glow of a hydrogen cloud

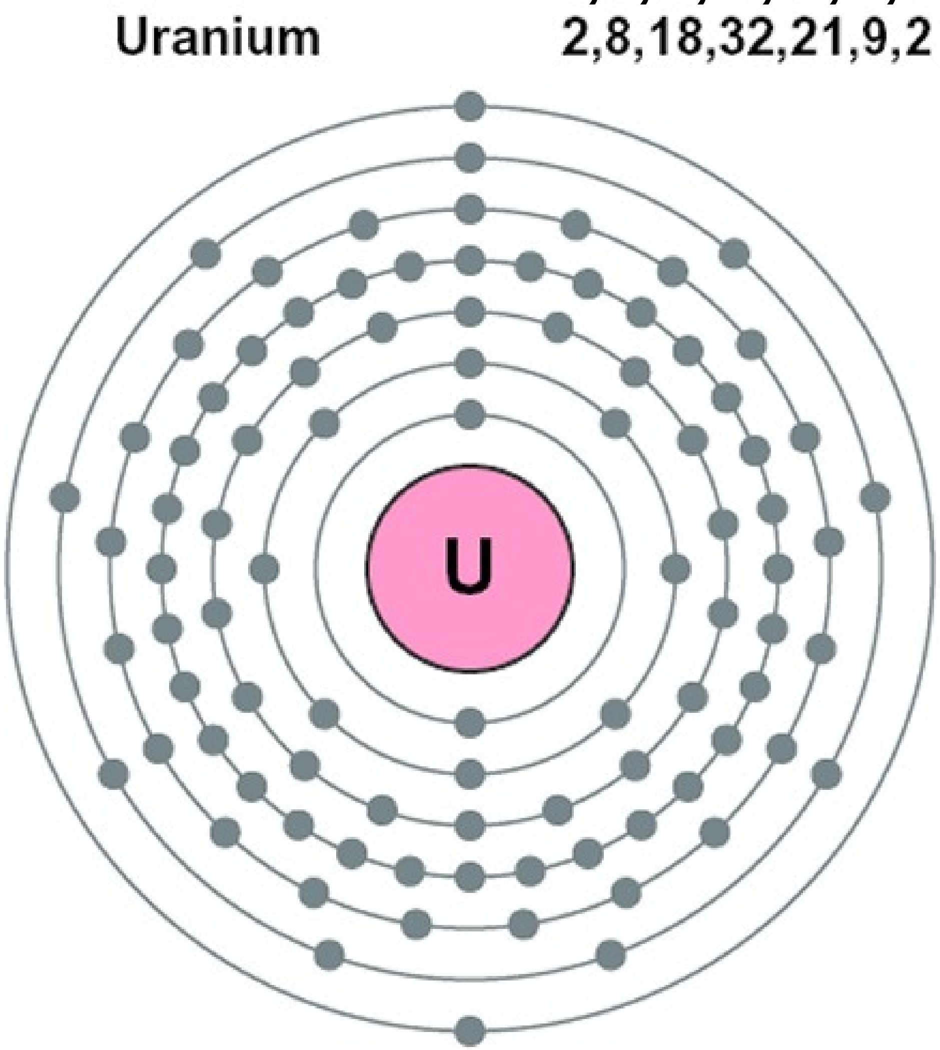
Quantum numbers and electron shells

- An electron is characterized by quantum numbers. These can be measured without uncertainty.
- The quantum number n labels the energy level E_n.
- The lowest energy level with $n = 1$ is sharp ($\Delta E = 0$), because an atom is stable. One can take an infinite time ($\Delta t = \infty$) to determine its energy and thereby satisfy the uncertainty relation $\Delta E \cdot \Delta t \geq h/4\pi$.
- n is related to the number of wavelengths that fit into Bohr's electron orbit (Slide 3). All orbits with the same n form a spherical shell. Since the size of a shell increases with n, outer shells can hold more electrons.

The shell model of atoms

Each shell corresponds to a certain quantum number n.

1,2, 3, 4, 5, 6,7 n



electrons/shell

A shell can hold $2n^2$ electrons.

Inner shells are filled first.

The periodic table of elements

Each shell *n* corresponds to a row.

Each row is filled from left to right.

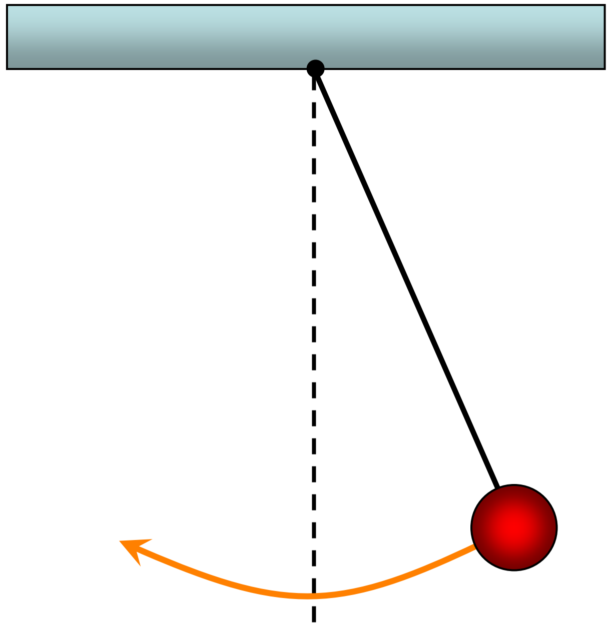
The number in each square is the Atomic Number, which is the total number of electrons in the atom.

n																																
1	1 H																														1	2 He
2	3 Li	4 Be																								2	5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg																								3	13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca														3	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr														4	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Uut	114 Fl	115 Uup	116 Lv	117 Uus	118 Uuo

This part is usually split off to make the table more compact.

Oscillating atoms in molecules

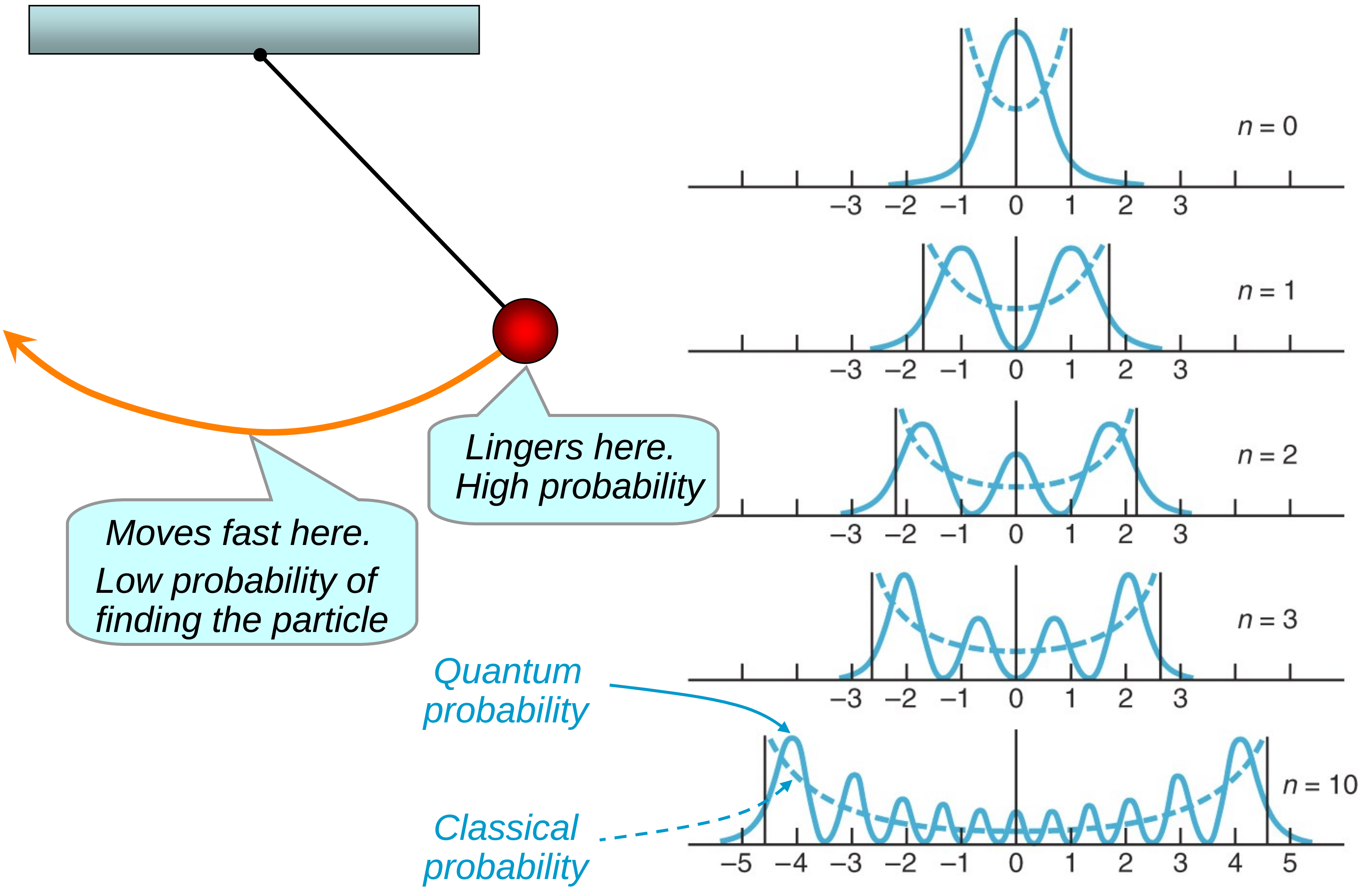
Oscillations of atoms in a molecule cause absorption / emission of infrared photons, for example by greenhouse gases (Lect. 10).



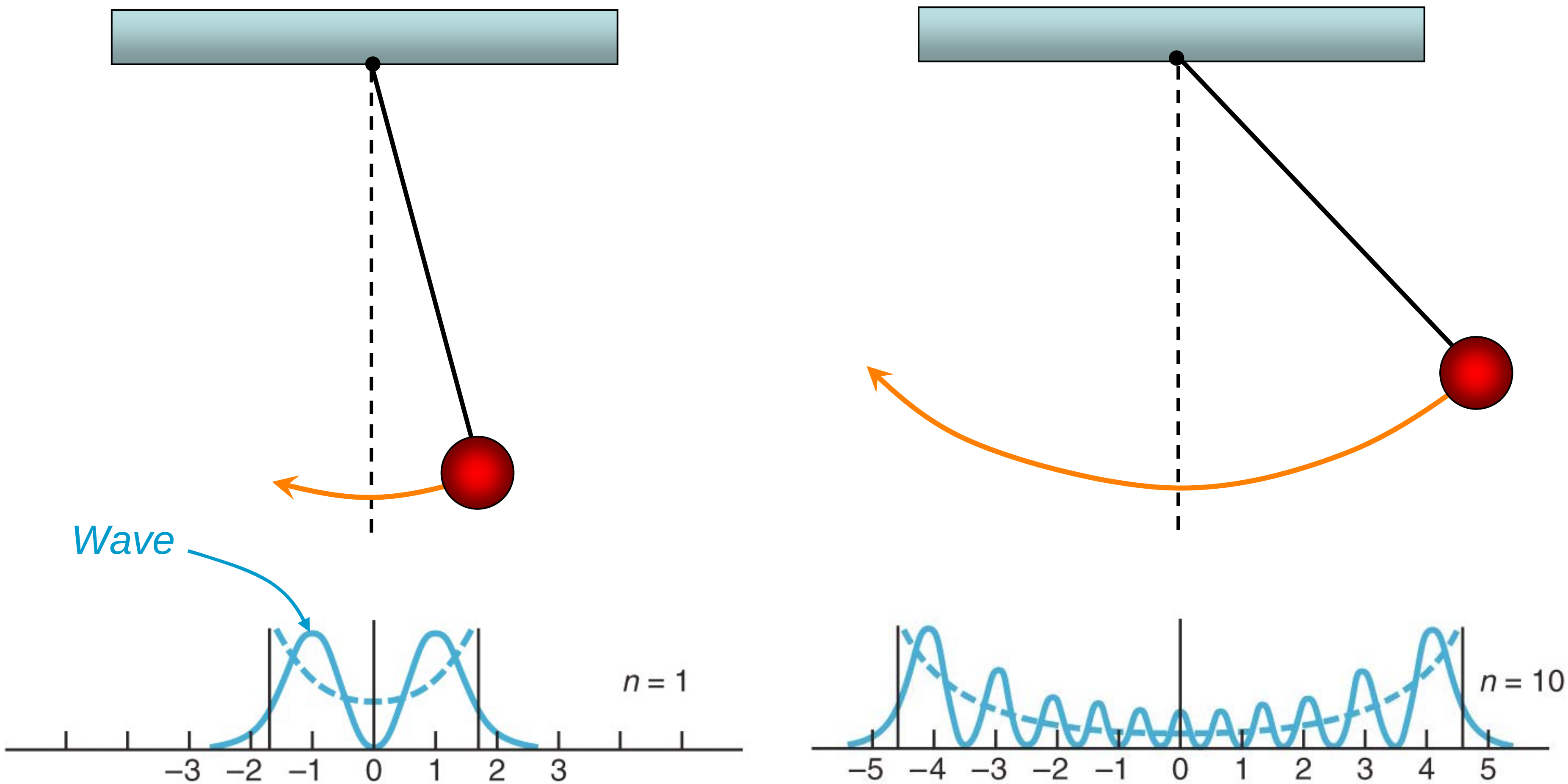
Pendulum and spring as classical models for oscillating atoms.

In quantum physics , atoms are wave packets (like electrons).

Atoms are described by wave packets, too



Classical *vs.* quantum picture

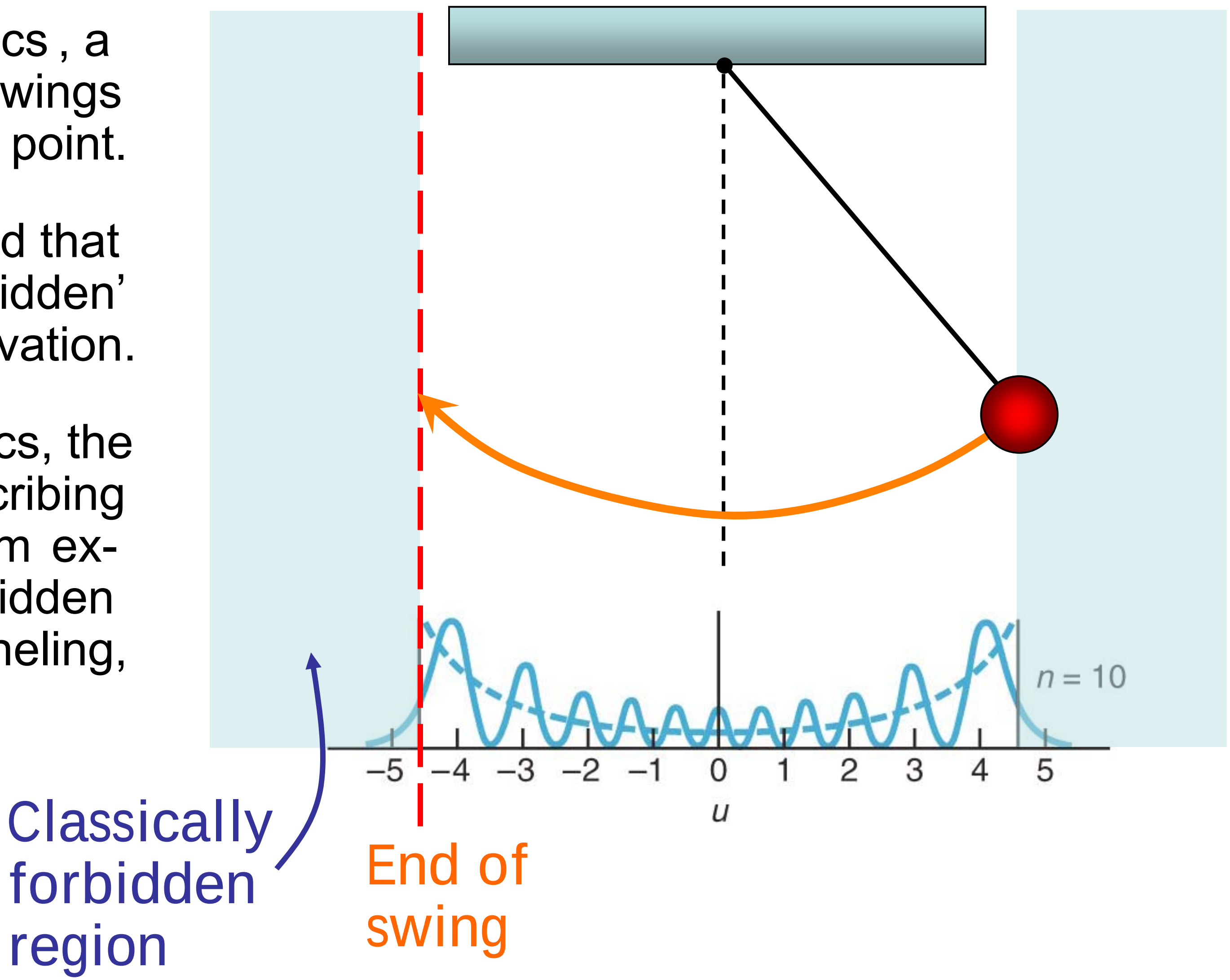


Small excursion
at low energy

Larger excursion
at higher energy

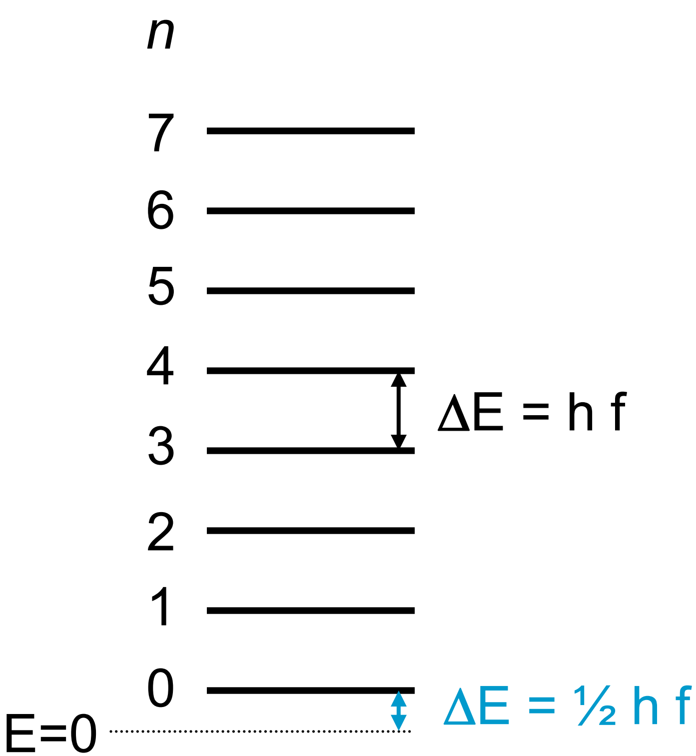
Classically forbidden regions become accessible in quantum mechanics

- In classical physics, a pendulum never swings beyond a farthest point.
- The region beyond that is 'classically forbidden' by energy conservation.
- In quantum physics, the wave packet describing an oscillating atom extends into the forbidden region. (See tunneling, Lect. 24a).



Zero-point energy

Energy levels of a quantum oscillator with frequency f .



- Even the lowest energy level has nonzero kinetic energy, the zero point energy.
- Atoms never sit still.
- An atom sitting still at a point would violate the uncertainty relation: $\Delta p=0$ *and* $\Delta x=0$
- Theorists are trying to explain dark energy as the zero point energy of elementary particles, but so far without success.