The Hydrogen Atom and Energy Conversion

The hydrogen atom

The hydrogen atom (H) consists of one electron of charge $-e$, where $e = 1.6 \times 10^{-19} Coulomb$, and one much more massive proton of charge $+e$. The electron moves about the proton much more rapidly than the proton wanders through space. The diameter of the electron is too small to be measured, but the diameter of the proton is about $10^{-15} m$. For such small particles, one cannot think in terms of a "classical" orbit, such as that of the moon around the earth, because small particles also behave as waves. The concept of wave-particle duality leads to the conclusion that the instantaneous location and velocity of the electron about the nucleus cannot be measured exactly. Thus, we do not describe the hydrogen atom as an electron neatly orbiting a proton but rather in terms of the probability of finding the electron at a position near the proton. Solving the fundamental equation of quantum mechanics for the hydrogen atom yields a probability distribution that describes the confinement of the electron to within about $0.05nm = 0.05 \times 10^{-9} m = 5 \times 10^{-11} m$ around the proton.

Unlike classical or macroscopic physics, quantum physics tells us that the electron in the H atom can have only discrete, as opposed to continuous, values of the total energy, which is the sum of potential and kinetic energies. By convention, we take the energy of the H atom to be zero when the electron has been moved to a great distance from the proton and is said to be free. The H atom is then said to be ionized, that is, its one electron has been removed. When the electron is not free but bound to the proton its energy can only be a value given by

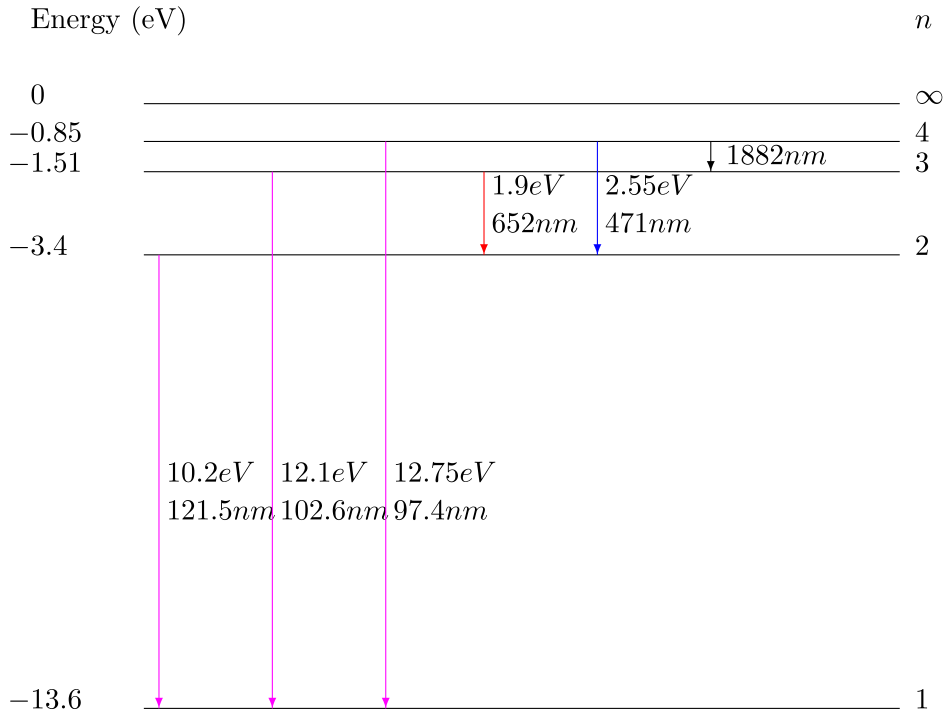
$$E_n = -\frac{13.6eV}{n^2}. \tag{1}$$

The electron volt (eV) is the unit of energy defined as the increase in potential energy of an electron of charge $-e$ when it is moved it is moved such that the electrostatic potential it experiences changes by $-1\,Volt$. Thus, $1eV = 1.6 \times 10^{-19} Joule$. The index n is called the quantum number, an integer from 1 to ∞. A "state" of the H atom is defined by the value of n or E_n. The state of lowest energy, known as the ground state, occurs for $n = 1$ and the state of ionization occurs as $n \rightarrow \infty$. A state with $n > 1$ is referred to as an excited state of the atom. The ionization energy, that is the energy required to remove the electron from the proton when the electron is initially in the $n = 1$ state, is $13.6eV$. If the value of n happened to be 2, then the energy required to ionize the atom would be only $13.6/2^2\,eV = 3.4eV$. The energy of the atom is defined as the energy of the electron given by equation 1.

Interaction with electromagnetic radiation

The energy of the atom can be changed by allowing it to collide with another object or by the absorption or emission of a photon of electromagnetic radiation. In either case, the energy of the atom can change only by a quantized amount given by $\triangle E = E_{n_{final}} - E_{n_{initial}}$, where n_{final} and $n_{initial}$ are the values of the quantum number n after and before the change in energy occurred. When a photon is responsible for the change in energy, only a photon of a particular frequency ν such that $h\nu = \triangle E$ can be absorbed or emitted. The quantity h is the Planck constant, and $h = 6.627 \times 10^{-34} JouleSec = 4.14 \times 10^{-15} eVsec$. It is useful to remember that a photon of wavelength $1242nm$ has an energy of $1eV$ and that the energy is inversely proportional to the wavelength, and vice versa.

Pictured below is an energy level diagram of the H atom. The downward arrows indicate emission of photons. The length of an arrow is proportional to the energy of the photon emitted.



Energy conversion concepts

When an electron and a proton are brought together, that is when the electron is moved in from infinitely far away, the atom will seek a state of minimum energy, the ground state of $-13.6eV$. There must be a mechanism by which this energy can be dissipated or else the electron will just pass on by the proton and never bind to form the H atom. One mechanism is emission of a photon. The conversion of the internal energy of the H atom into a single photon is a reversible process. The atom in its ground state can absorb a photon as readily as an atom in an excited state can emit a photon. Another mechanism of energy dissipation is that of a collision with one or more objects. Collisions result in the transfer of energy as heat. Via collisions the internal energy of the H atom can be changed into the disordered energy of molecular motion (translations, rotation, vibration). This is not a reversible process. The energy transferred from the atom as heat cannot be transferred back into the atom completely.

The question arises as to how to best convert the energy of a separated electron and proton into useful work and a ground state H atom. If the two particles are brought together while enveloped in a gas, the energy released upon binding will be transferred to the gas as heat, and the hot gas can be used subsequently to run a heat engine with the usual thermodynamic limit to the efficiency. If the desired form of energy is electromagnetic radiation, then bringing the two particles together in a vacuum will result in the emission of one or more photons with a total energy of 13.6 eV. If the desired form of energy is electrical, then one could imagine allowing the electron to pass through wires and a motor on its way to the proton. Though impractical for the hydrogen atom, this concept is the basis for the efficient conversion of chemical energy to electrical energy achieved in fuel cells and batteries.