Quantum Prehistory:

Radiation from Objects: Remember from 317K that for an incandescent object,

$$\mathcal{P} = \varepsilon \sigma A T^4.$$

The peak frequency of emission is proportional to T.

Attempts to understand this using Maxwell's equations led to catastrophic failure. Max Planck (1858 - 1947) solved the problem by fitting an equation to the observations and then guessing a relationship from which the equation could be derived. The key new assumption was that the radiation was emitted by oscillating charges whose energy and frequency of oscillation were related by $E = hf$, where h is a universal constant, Planck's Constant.

The power density for an object of surface temperature T is (in Watts per cubic meter):

$$R = \frac{2\pi hc}{\lambda^5(\exp[hc/(\lambda kT)] - 1)}.$$

Photoelectric Effect: When light shines on a metal surface, the light can knock electrons out of the metal, but physicists were baffled that the kinetic energy of the electrons knocked out was *independent of the light* *intensity,* in other words, independent of the electric field maximum. Albert Einstein (1879 - 1955) was able to understand the results by assuming that light consists of particles, which he called photons, and that for such photons the kinetic energy is $K = hf$ and the momentum is $p = h/\lambda$. Collisions between individual photons and electrons knock the electrons out of the solid.

Compton Effect: Arthur Holly Compton (1892 - 1962) directly observed elastic collisions between X-ray photons and electrons. Conservation of relativistic energy and momentum gives the correct relationship between the shift in wavelength of the scattered X-ray photons, and their angle of scattering θ relative to the incident direction.

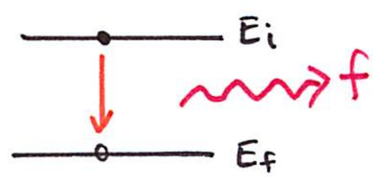
$$\Delta\lambda = (h/(m_e c))[1 - \cos\theta].$$

Hydrogen Atom Energy Levels: It was obvious from the fact that excited atoms emitted light of only specific frequencies that atoms must have "discrete" energy levels, like the rungs of a ladder. Niels Bohr (1885 - 1962) invented a model of hydrogen in which electrons impossibly orbited the nucleus because their angular momentum was quantized in units of $\hbar$ (h divided by 2π). That is, $L_n = n\hbar$, with n an integer equal to 1 or more. Given the potential energy between proton and electron as $U(r) = -k_e e^2/r$, the result was that the only allowed energies for the orbits actually matched the observed hydrogen spectrum:

$$E_n = -\frac{(k_e e^2)^2 m_e}{2\hbar^2 n^2} = -(13.6 \text{ eV})/n^2.$$

Transitions between energy levels result in emission of photons of frequency f such that

$$hf = |E_i - E_f|.$$



For a one-electron atom with Z protons in the nucleus, just multiply the Bohr E_1 by Z^2 for an estimate of the ground state energy. Bohr was well aware that electron orbits are actually impossible. An orbiting electron would be accelerating continuously, and therefore radiate continuously. In orbits at atomic scale, electrons would radiate away their entire energy in a tiny fraction of a second, and atoms could not exist!

Matter Waves: Louis de Broglie (1892 - 1987) postulated that the relationships $E = hf = \hbar\omega$ and $p = h/\lambda = hc/f$ work for all particles in nature. His idea was confirmed by the observation of electron diffraction. The big question, of course, was "what is waving?" de Broglie had no helpful ideas there.

Uncertainty Relations: Werner Heisenberg (1901 - 1976) pointed out that the wave nature of matter results in unavoidable limitations on the kinds of information that can exist in nature. A simple expression of the limitations is given by

$$\Delta x \Delta p_x \simeq \hbar, \text{ and } \Delta E \Delta t \simeq \hbar.$$

The idea is that for quantum systems, determination of position destroys existing information about momentum, while determination of momentum destroys existing information about position. Similarly, determination of the total energy of a process destroys existing information about the time it takes for the process to take place, or when it took place, and vice versa. Note the energy-time relation can also be written $\Delta\omega\Delta t \simeq 1$.