Lasers

An interesting application of the energy levels in atom is the laser. We'll discuss it now to learn about it, and as practice with energy levels.

Suppose you have an atom with a ground state of -20 eV, and a first excited state of -15 eV. (Purely hypothetical to illustrate the idea).

That means that:

1). A 20 eV photon can ionize the atom, i.e., push the electron above $E=0$ where it is free.

2). A 5 eV photon can be absorbed to make it "jump" into the excited state.

After some time, the excited atom will spontaneous emit a 5 eV photon and relax into the ground state.

As we saw in the Franck-Hertz experiment, an energetic electron can also excite the atom...
A glass tube filled with a low pressure gas of our hypothetical atom will give off 5eV light.

If V > 5 then still glows, because some electrons will transfer 5eV to atoms.

The emitted light will be monochromatic (all one color, i.e. all one wavelength).

But, it will be random in direction, polarization, and time of emission.

This is the idea for a neon light.

A laser is this, plus more...

LASER = light amplification by stimulated emission of radiation.

So, what is stimulated emission?
Stimulated emission (as opposed to spontaneous emission) is when an excited atom emits its photon due to "stimulation" with another photon.

In our example, an atom in the excited state will be induced to radiate (emit) a 5 eV photon when struck by another 5 eV photon.

Both photons go out, and they are coherent, meaning same frequency, polarization and phase. \Rightarrow AMPLIFICATION

So, this stimulated emission "amplifies" the light in a coherent way -- not just brighter, in phase.

That coherence is what makes lasers useful, for example, to cut, or even to point since it is a dot.
So far, we've talked about one atom. There are many, and potential stimulator is much more likely to be absorbed by a ground state atom than find an excited atom to stimulate into emission.

To get useful amplification, we need to have a lot of excited atoms -- in fact we need more excited atoms than ground state atoms.

Normally there are more ground state than excited. More excited than ground is called "population inversion".

So, to get LASE-ing we need to invert the population by pumping in energy, we can do that by flashing it, running a current through, etc.

Then, we wait for one atom to spontaneously emit. It will stimulate an amplifying cascade.
To get the light going in the direction we want, just put mirrors on the ends to give properly directed photons repeated chances to stimulate.

If time allows, describe the He→Ne energy transfer in a HeNe laser, metastable states, etc.
Wave nature of particles

We've spent the last n week seeing how light behaves as a particle as well as a wave.

So... do particles likewise behave as waves? That would be symmetric...

The answer is yes. And, we'll discuss that now. First, let's try to reason through it as was done long ago, originally.

For light, $E = hf = h\frac{c}{\lambda}$.

What is momentum? Well, relativistically,

$$E = \sqrt{p^2c^2 + m^2c^4} = pc$$

for a photon.

So, $p = E/c = h\frac{c}{\lambda}/c = h/\lambda$.

If we try to apply these:

$E = h\frac{c}{\lambda}$ and $p = h/\lambda$

to a particle, it is not clear what $E$ to use, and $f \neq c/\lambda$. But, $p = h/\lambda$ is simple.
So, in 1924 Louis de Broglie proposed that particles also have wave properties with 

\[ \lambda = \frac{h}{p} \]

Let’s test this: take a car, ~1000 kg, moving at 100 m/s, what is its \( \lambda \)?

\[ \lambda = \frac{h}{mv} = \frac{6.626 \times 10^{-34} \text{ J.s}}{1000 \text{ kg} \cdot 100 \text{ m/s}} \]

\[ = \frac{6.6 \times 10^{-34}}{10^5} = 6.6 \times 10^{-39} \text{ m.} \]

That is a small number... untestably small.

But... take an electron and accelerate it through a 1 volt gap. What is its wavelength? First, we need \( p \). What is that?

\[ K = W = 1 \text{ eV} = 1.6 \times 10^{-19} \text{ J.} \]

\[ \frac{1}{2}mv^2 = K \Rightarrow p = mv = m \sqrt{2K/m} = \sqrt{amK} \]

Note that I’m not using \( K = (\gamma - 1)mc^2 \) or \( p = \gamma mv \). Is that OK? Yes, because \( K = 1 \text{ eV} < mc^2 = 511 \text{ keV} \).

Comment on “mass” in eV...
So, \( p = \sqrt{2mk} = \sqrt{2(511 \times 10^3 \text{ eV}) (10 \text{ eV})} \)
\[ = \frac{1000 \text{ eV}/c}{3 \times 10^{-8}} \]
\[ = 5 \times 10^{-25} \text{ kg m/s} \]

\[ \lambda = \frac{6.626 \times 10^{-34} \text{ kg m}^2/\text{s}}{5 \times 10^{-25} \text{ kg m/s}} = 1 \times 10^{-9} \text{ m} = 1 \text{ nm} \]

Our examples show that \( \lambda \) is non-negligible for atomic sized objects.

1 nm is not so small, only about a hundredth of typical visible light wavelengths.

How could we test this?

**Diffraction** —— interference effects from waves.

Just pass these electrons through a diffraction grating.

\[ dsin \theta = \lambda \] gives maxima.

\[ y = L \tan \theta = L \sin \theta \]

\[ \Rightarrow L \rightarrow \]

\[ \frac{L^2}{d} \]
If \( d = 1 \mu m \), \( L = 1 m \), \( y = \frac{1mm}{1\mu m} = 1mm \).
Right?

Well, \( \lambda < d \), so a weak pattern.

To see a strong pattern, we need \( d < \lambda \). How can you make slits \( < 1nm \) wide?
With atom spacings in a crystal.

In 1927, Davisson & Germer accidentally observed this... they unknowingly produced a single crystal in an electron scattering experiment.

Just like x-ray crystal diffraction.

\( \Rightarrow \) Electrons interfering like waves.

Wave \( \Rightarrow \) particle

Particle \( \Rightarrow \) wave

Wave \( \leftrightarrow \) Particle

"duality"
This electron interference is useful in an "electron microscope".

We treated light as "rays" in optics, but we saw that diffraction limits the resolution.

A slit smaller than $\lambda \Rightarrow$ spherical waves.

$\Rightarrow$ We can't resolve something smaller than $\sim \lambda$.

$\Rightarrow$ Make $\lambda$ smaller to "see" smaller objects.

Electrons are easy to give large $p \Rightarrow$ small $\lambda$

$\lambda = \frac{h}{p}$. 