Modern Physics notes – Spring 2007

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Lecture 4

- Photoelectric Effect
- Photons

- Fowler, "Photoelectric Effect"

The photoelectric effect

One very clear experimental way of seeing that light is a particle is via the photoelectric effect. This is very common in today's world: for example, this is what makes light-powered calculators work. The idea is simple: you shine light on a metal. The energy in the light is transferred to the metal, allowing the electrons to break free. If you attach wires properly, this gives an electrical current.

That doesn't sound so mysterious, but when you examine this effect more carefully, weird things happen. As in the modified double-slit experiment, the dependence on the intensity and wavelength is not what one would expect from classical wave physics. One finds that for light above a certain wavelength, there is no photoelectric effect, no matter what the intensity. This is just like the double-slit experiment, where for $\lambda > d$ the interference remained unchanged, no matter what the intensity.

In the photoelectric effect one also finds that the velocity of the emitted electrons is independent of the intensity. Turning up the intensity only results in more electrons, not faster ones. One finds experimentally that for a given light frequency $\nu = c/\lambda$, the velocity of an emitted electron v is given by

$$h\nu = W + \frac{1}{2}mv^2$$

where m is the mass of the electron, and the quantity W is called the work function. It depends on what metal is being used (and on various surface properties). $1/2mv^2 = KE$ is of course just the kinetic energy of the emitted electron. Note that this formula does not involve the intensity of light at all.

The amazing, experimentally testable, fact is that the h in this formula is the **same** as that we saw in momentum quantization. So how do we interpret this?

The correct way to think of this is as conservation of energy. Let's pretend light is a particle with energy $h\nu$. Then what this says is the the light hits the material, it takes some energy W to yank the electron away from the material. The leftover energy then goes into the kinetic energy of the electron. That sounds perfectly reasonable. But light is a particle!?!

Photons

Understanding the photoelectric effect and the "which slit" experiment requires light to be a particle. I emphasized before that even though they interfere, electrons still are particles in the sense that they appear in discrete lumps: you send one electron in, you get one out. Light is like that too. We call these particles *photons*.

A single photon has energy $E = h\nu$. This explains why long-wavelength light, no matter how bright, causes nothing to happen: there's not enough energy in a single photon to free the electron.

In visible light we usually see zillions of photons at a time, although it turns out that our eyes is almost sensitive enough (it's within an order of magnitude or so) to see individual photons. In the homework, you'll quantify "zillions".

So light behaves like a particle in some respects, and electrons behave like waves in some ways. In fact, we can see a very important common property of the two if we look at the momentum of an individual photon. It may not be immediately obvious that light has momentum, but think about it a bit. Light clearly has energy: you get a lot hotter sitting in the sun than if you sit in the shade. It has momentum as well: you remember that if you put a particle of charge q in an electric field, it feels a force $\vec{F} = q\vec{E}$. Light is a wave of electric (and magnetic) field, so light hitting a particle will put a force on it. Of course, putting a force on a particle changes its momentum (precisely, $\vec{F} = d\vec{p}/dt$), so by conservation of momentum light must have momentum as well. You can derive this from Maxwell's equations, but that's kind of tricky, because you have to deal with waves.

So how does the energy of a photon relate to its momentum? For a non-relativistic particle of mass m, we have $E = 1/2mv^2$ and $p = mv$, which gives

$$E = \frac{p^2}{2m} \qquad\qquad v \ll c$$

You can see experimentally (and from Maxwell's equations) that this does not apply for light. What one does find from Maxwell's equations, or by experiment, is that

$$E = pc \qquad\qquad v = c$$

If you've never done relativity before, you may not have seen this formula, but it is simply the energy-momentum relation for a particle with no mass. A photon is a particle with no mass! Plugging in the above formula, and the relation of frequency to wavelength, we have for light

$$h\nu = E = pc$$

Using the fact that $\lambda\nu = c$, we have

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

This is the same relation we had for an electron! So in fact $p = h/\lambda$ applies to both photons and electrons (and in fact all particles). Note however that $E = h\nu = hc/\lambda$ *only* applies to massless particles like photons. So be careful which formula you use!

So we now see why the results of the "which slit" experiment depended on the wavelength of the light. First note that in order to see interference, the wavelength of the electrons needs to be about the same as the distance between the slits d. So now think about photons with wavelength a larger than d. As we said before, then there's no way we can tell which slit it went through: the light can't resolve the slits. Now think about photons with a wavelength λ smaller than d. This means that the momentum of the photon is larger than that of the electron:

$$\frac{h}{\lambda} = p_{photon} > p_{electron} = \frac{h}{d}$$

When the two scatter, the photon drastically effects the electron. It thus effects the experiment substantially: we're no longer doing the original experiment, and it's not shocking that the interference goes away here. For $\lambda > d$, the opposite happens. The photon has much less momentum than the electron, so they don't disturb the electron much. The interference pattern remains.

One subtlety: in both cases, the process (in the photoelectric effect, emitting an electron; in the "which slit" experiment , it's disturbing the electron) must involve only a single photon: you can't have two photons affect a single electron. This is reasonable: the processes happen very quickly, so both photons would have to hit the electron at the same time to both affect the process. Einstein didn't know how quickly the processes happened, but assumed it to be true. It does seem plausible, I hope. Now the reasons why the process is so quick are understood, but involve much more advanced methods: but the upshot is that the way electrons and photons interact is basically one electron and one photon at a time.

Einstein got the Nobel prize for this explanation of the photoelectric effect, providing confirmation of the existence of the photon. (Planck earlier had postulated this by studying black-body radiation, which we'll get to down the road.) Even more amazingly, his paper was in 1905, the same year as his paper on special relativity and another major paper explaining Brownian motion. When he got the prize, relativity was still too weird for some people, so they gave him the prize for the photoelectric effect. Ironically, later in his life, Einstein was very unhappy with quantum mechanics, believing that it was only an effective way of viewing things. Also down the road, we'll get to some of these objections (the EPR "paradox").