Student Understanding of the Photon Concept: Faculty Expectations

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What a photon is:

(F) I don't really have a mental picture. Yeah. That's right, I don't have such a mental picture of, like here's a light beam as a stream of photons or anything like that. Because it's just too easy to get screwed up, when thinking about that. ... I probably see a Feynman diagram, with an electron emitting a photon, or a Compton scattering diagram or something like that.

(D) I would describe it as a quantization of light. I can associate a particular energy, and the energy is related to the color or frequency, and the idea that in certain kinds of experiment, light waves would not be terribly useful. You could actually count photons, one, two, three, four, as they come in.

(L) I actually see some sort of a shadow, it's yellow. Again, my mental image is it's about the size of a dime; it does have a shadow, but it doesn't have any mass.

(V) I have this mental image, which is what I draw all the time, which is like a little squiggly arrow, like a little sine wave with an arrow at one end.

(B) When I hear photons, I think of the photons that you see in collider experiments are energetic things that leave certain tracks in calorimeters and I see little bullet flying out of this collision that does things that create e-plus, e-minus pairs inside this dilinear thing, the picture I have is little high energy bullets flying out of a collision.

(P) I think a big empty space that doesn't have any matter in it, it's just like an infinite space with no matter in it, then I guess ... every time you have a photon you have to think about what are the boundary conditions, cause like a photon that would be in a metal cavity would just be some electric and magnetic fields that are oscillating and you can think of it all being confined within that cavity.

(Y) A photon is a packet of energy that represents light in its interactions with matter. It delivers energy to the matter that is proportional to the light's frequency. It can cause an electron to jump to a higher excited state in processes of absorption when it has the right amount of energy for the jump or it can free (ionize) an electron if its energy is high enough to overcome the Coulombic attraction to the nucleus or lattice with which the electron is associated. A photon can be released when an electron jumps from a more excited energy level to a less excited one through emission. This emission can be spontaneous or stimulated.

R. Kidd, J. Ardini, and A. Anton, *Am. J. Phys.* **57**, 27 (1989), "Evolution of the modern photon" shows the various models of the photon, and how they fit together.

How would you explain a photon to a nine-year-old?:

(P) (I)f you have very, very dark room, how little light can you have. What's the least light you can have? And it turns out that light comes in little lumps and a lump, you can't have 1/2 a lump, you can't have 1 1/2 lumps, and those lumps are called photons, and then I'd say ask your mother. I think you'd have to go to graduate school to be able to understand much of the rest of it.

(F) One could imagine asking, doing a thought experiment, and you have a source of light, and you turn it down, lower and lower. And could you get to the point where, can you just do it continuously lower and lower and lower and lower so that the intensity goes down as small as you want?; the brightness, or whatever you want to talk about. And then introduce the idea that there's a minimum level, and that's the photon. If you had some, some source, the minimum thing that you could actually emit some kind of light that you could detect somehow. Talk about detector, like your eye is a detector. Talk about an eye is a detector of light, it comes in, and, some chemical change, cell reacts and sends a chemical signal to your brain and you know there's some light there. The absolute minimal thing that could do it, would be a single photon. And if we go backwards, and as you interpolate up, what you're doing is getting more and more photons.

(D) I’m not sure I’d go down to photoelectric effect. My guess is that many pieces of that are too subtle. I think I would tell them that if they had really good eyes, and they went into a dark room ... so if they had really good eyes and went into a dark room, and one started to turn down the lights that way, it would get darker and darker and darker in a continuous fashion, and then what you would find is, since there are photons, if the number of photons would become small enough, that you’d see the flash of one photon, the flash of the next photon, and as you continue to turn the lights down, the flashes would stay the same brightness, but you’d just get further and further apart. The color of them would stay orange, or blue, or red, whatever it is, no matter how far down you turned it, you’d see flashes. There might be some problem about you lose your color vision in near dark, but I gave you infinitely good eyes.

(V) If you only have a few words, which is what you only have when you're talking to a younger kid, you only have a few ideas that you can get across. If you can only pick one main idea about the photon, in some descriptive way, what is it? And for me, it's this chunk. But you've got to be careful with that. And then that's not all there is. I don't know, I don't really have a good one yet.

(B) I would just say it’s a particle of light. Light is actually made up of little particles. Like stuff is made up of little particles called atoms, light is made up of little particles called photons.

(Y) I would start by talking about matter being made up of elements, move to atoms and molecules (water), then talk about atomic structure, middle school kids are ready for this in general. Then we would talk about the electron clouds around the nucleus and how they gain and lose energy to make different paths more likely about the nucleus. Then we would talk about the stuff above: ways to absorb or emit energy. ... which include photons (or light). We would look at the spectra of a gas tube with a diffraction grating (very cheap from scientific houses) and discuss the lines and the energy level changes they represent.... From there we would discuss how the electrons in the gas tube got their energy and how they gave it up...... etc. This would move into photon character of light. There are some cool computer simulations of double slits that could be used to compare to exposure of a film and show photons striking the surface to form the interference fringes that could also be used, ... but spectra are the easiest in terms of energy and packets of energy.

(L) For a nine-year-old, when you're describing a photon, you learn about a lot of stuff. Physics 131-132, you have to back off and unlearn that stuff. So if you just start off with a photon, without the baggage you bring from 131 and 132, some of these questions you ask, "Can a photon exert a force?", is not a hard question for a nine-year-old, but because of the baggage you bring, for example, you know about mass and kinetic energy, and stuff like that. They start getting away from the simple notions. Just describing it as a particle of light, a little piece of light, they have no notion what a piece of light is anyway, so you tell them it's a particle of light. There would be some confusion, I think, because you see motes of dust. You somehow might think those are photons. But, you're not going to have such a hard time describing it as particles; I don't think they'll be bothered.

What should we put into our courses about quantization and the photon?:

(F) Until you start talking about quantum phenomena, it's less useful to have the photon than the wave properties and to focus on knowing, how waves behave. ... And you could talk about different colors. ... the photons have different energy, and different ability to do things. ... Where it's easiest to see how to get my single photon, is having a single atom, molecule, whatever, with this idea that they can have, that they're discrete when they gain or lose energy. When they lose energy, they can do that by the energy carried off by a single photon. They should have some just basic idea about the quantum ideas, about things being quantized. And that the photon is the quantum of light. It has energy and momentum associated with them, that are associated with the other properties of light: wavelength and frequency and speed. ... I think they should be familiar with experiments ... in which photons are, the individual photon nature plays a role, like photoelectric type things, which is very important. ... They should be certainly aware of the connection with atomic and other transitions; its mechanisms for light, and the photons associated with those transitions.

(V) I think at a lot of levels, having some understanding of electromagnetic radiation, just from the wave point of view I would be happy with as a start. And then go into the idea of this photon, these chunks of light.

I mean, obviously, there are some, some really important things with lasers, that really kind of depend upon this idea of photons, a collection, a large collections of photons that are in everyday life. In CD players, in all kinds of things. Laser surgery, and so that, if you understand a little bit about normal electromagnetic waves and then, introduce the idea of these chunks of light, with sort of this modern spin on it.

(B) You have to know that a lot of photons put together behave like electromagnetic waves that obey Maxwell’s equations and so they show interference and so on... The photons have energy and momentum and energy momentum determines the color of the light. when you make a wave out of them....As the photon is absorbed its energy-momentum is absorbed by the material. ... and that they interact, they have point-like interactions. ... and the wave nature is that when you put a lot of them together, they behave like waves described by Maxwell’s equations. and they can interfere with that. ... it’s worth knowing that light has polarization as well as a basic property.

(D) (Y)ou’ve reminded me that there are lots of x rays and things, and it seems like if you’re going to be in the business that uses x rays, at some level have to worry about health safety and all those things, one ought to have some good idea of the relationship between energy and color, ought to understand what color means, getting up into the x rays. I suppose this may be hoping too much, but it would be nice for them to know that the energy of the x ray is enough to break the chemical bond. And understanding what it is in electronvolts compared to the electronvolts of a bond.

(P) And even if you go read Feynman's lectures, he talks about the quantum aspect of measuring things, how he says if you think you understand that either you a greater genius that Feynman or you don't get it. so anyway, you probably don't want to tell people nothing. It'd be nice to understand some experimental facts about how when you detect, as a practical matter, when you detect high energy photons that you usually detect them in discrete lumps and that you can only have N photons an integer number ... I guess I want to have a lot of disclaimers. I really don't think that you do understand this now, after we've told you these things, we're teaching you at the level of, if you read, uh, reading the New York Times and think you understand something about (about cloning sheep) but to think you really understand how that works, you'd probably be misleading yourself.

(Y) (S)ome historical development that goes with the modern atom and our picture of it. The quantum mechanical atoms, how the photon interacts with them, was to think about the photon/wave nature of light, bunches of demos/experiments on the topic, how this relates to lasers...

(L) What is the point of what we're doing right now? In 111 and to a lesser extent 112, it's fairly easy. We're teaching them a way to think. It's fun. Not that they're necessarily going to use this stuff, but it's useful. In 113, there's no direction, not really very clear where Giancoli's going and what he thinks about it. That's certainly my reading of it.

General comments:

(F) I have a stack of modern physics books. There is no good explanation of photons, other than ... No good explanation of photon. Stop. What there is are statements of properties and things like I’ve given you.

(V) X-ray machines, themselves. How’s a photon relevant to that? Well, an x-ray machine basically consists in taking an electron beam and bashing it into some material, and in so doing, you excite the electrons, rip a bunch of them off the atoms, and so forth. You make holes inside these sort of things, and as the electrons rattle down, they give off specific chunks of light. Give off photons. So you end up with x radiation of specific wavelengths, line radiation that would typically come off, then with some background underneath it.

I guess, I guess that’s a pretty good demonstration of a photon, isn’t it? The line radiation.

(P) Setting aside quantum measurement, which is very difficult to understand, you can say that light comes in bundles, discrete bundles or discrete lumps—you can't have half a lump—and when the lumps get really big, which they do when you have x rays and gamma rays, it has real consequences. You actually measure it coming in lumps. If frequencies are smaller, the lump size is so small and you have to have so many lumps to detect anything, that it just seems like you're getting a continuous stream, like a river is made of molecules.

So you're thinking that the water analogy is like raindrops pelting down?

There you go. Yes. That's good.

(D) (O)ne of the biggest problems out there is the misunderstanding of how to use the term radiation to go from microwaves to x rays. In fact, there’s a cartoon in the newspaper the other day that illustrated this problem. You may recall the last several weeks there’ve been discussions about the FDA approving irradiation of meat. As you can imagine, there are a lot of people who worry about the radiation. The cartoon was showing a guy bitterly complaining about the irradiation of meat and the supposed irony of this was he was cooking his meat in a microwave. The cartoonist obviously didn’t know the difference between microwave radiation and nonmicrowave (ionizing) radiation. What are the issues? It’s kind of important to make people understand these issues.

(L) One question you asked, if it changes direction, is it the same photon? In Rayleigh scattering or Compton scattering, we generally think it is the same photon. Then, you can back up from that and say, let’s talk about fluorescence. In fluorescence, you get a photon out of a different color than the one you put in. And of course you do the same thing in Compton scattering.

Consensus:

Different models are appropriate at different levels.

Physicists have the same sort of variety of models in mind as students, although they may be generally more sophisticated and elaborate. These models range from thinking about photons in terms of creation and annihilation operators acting on the vacuum (very formal) to visualization of actual particles.

Suggestions about courses:

No total agreement on what we should be teaching—but we descry some agreement from our interviews:

- photons should be taught because they're such a good example of quantization
- particle and wave nature of particles and light
- quantization of energy and momentum transfer in collisions involving light

This is what we've heard, not what we advocate (yet)!