More confusion

Models of the Atom

At about this time there were two detailed pictures or models of the nature of the atom. The first and in some ways simplest one was that the negatively-charged electrons of the atom circled around the positively charged centre, which contained most of the atom's mass. This picture was suggested by analogy with the solar system; after all the gravitational force holding the solar system together is exactly the same in mathematical form as the electrical force, which we know controls the atom. This picture came to be known as the Rutherford atom.

However, there was a problem with this picture. If the electrons circle around the positive charge then to something far away they are exactly like our oscillating dipole. They must be generating electromagnetic radiation. But, as we know, that radiation is carrying off energy, which must be provided by the moving electrons themselves; they must lose kinetic energy. If they do that, they will be pulled closer to the centre of the atom. But since this radiation will still go on, they will continue to fall in towards the centre and must surely collapse into nothingness, all their energy being radiated away! The model appears to give a basically unstable atom.

To avoid this radiation collapse problem an alternative model was proposed. It was hypotherized that the positive charge was not concentrated at the centre, but was very large and diffuse, spread over the whole volume of the atom and inside this positive charge the electrons existed. In this way the motion of the electrons became unnecessary (in a sense they had already fallen into the centre!) as a detailed calculation (or some straightforward thinking) shows that there will be no force on an electron at the centre of the atom. Furthermore several electrons can be accommodated since even though they will push each other apart, they will still be kept inside the atom. This model very nicely avoided the anticipated problem of radiational collapse, and in fact had every appearance of agreeing with all known properties of the atom. The picture was given the rather descriptive name of "the plumb pudding model".

We can discern a very clear cut difference in the properties that an atom should have according to these models, and through this should be able to experimentally distinguish between them. It concerns scattering of energetic charged particles off atoms. To see this we can make use of our potential picture. Let's make an energy picture of a charged particle scattering off the positive part of the atom, as indicated by both models. In the one case the positive charge is concentrated at the centre, so that at that point a very strong repulsion should be felt by a positively charged particle coming towards it. For the plumb pudding model, the positive charge is spread all over the atom, so that the same charged particle would at no place be as strongly repelled by the atom as it would at the centre of the Rutherford atom. If we choose a high enough energy particle (and we can easily calculate the energy required) the two models predict a completely different behaviour for the scattered particles. With sufficiently high energy particles the plumb pudding model predicts that <u>all</u> scattered particles will carry on in much the same direction as they started, and will only temporarily be slowed down by passing through the atom

However, for the Rutherford atom, if there is a head-on collision or very nearly so, the particle will be stopped, and "bounced" back.

The two models predict a completely different behaviour for the scattering of the same atom. The plumb pudding model predicts that *only* forward scattering should occur, while the Rutherford atom predicts that large-angle, or backwards scattering must occur. If we *do* this experiment we should be able to confirm *unambiguously which model is correct*!

In fact just this experiment was done by Rutherford at the turn of the century. In order not to worry about the influence of electrons (which we haven't even considered in our comparison) he used Helium particles with their electrons removed. He bombarded gold atoms in a very thin foil, so that only a few atom collisions were involved. His results conclusively showed that a number of the particles were scattered through very large angles. Therefore all the positive charge of the atom must be concentrated *at the centre of the atom*. The atom does *not* look like a plumb pudding after all, but more like a planetary system of electrons circling around the central positive charge, which we now call the nucleus.

But this means that we have to face up to the problem of radiation collapse! The reason the plumb pudding model was invented was to avoid radiation collapse and we have just thrown it out. Perhaps the collapse occurs so slowly that we don't notice it at all. Maybe all material is slowly shrinking away. No - the collapse is calculated to occur in something less than 10^{-8} seconds - and yet it doesn't happen; we <u>know</u> it doesn't happen, or we wouldn't be here now. Once again we are faced with a dilemma. We set out looking at the atom to see if we could solve the problem brought on us by the ultraviolet catastrophe and have run smack into another one - atoms that should radiate themselves away, but don't! Perhaps this is really the same problem, but clearly we haven't got any farther with it. Where do we go next?

The Photoeffect

The two problems we have, high frequency radiation and the motion of atoms are certainly connected, but exactly how is far from clear at this point. About the only thing we can really do is collect as much information as we can about radiation and atoms and hope that eventually some solution to our problems can be found.

It had been observed for some time that electrons could be ejected from certain metals by shining ultraviolet light on them.

This effect, called photoemission, or the photoeffect, is understandable in principle, as we recognize that the light carries energy, and the electrons are bound to the metal by some amount of energy, so that if we pump enough radiation energy into the metal (heat it up) we should raise the temperature sufficiently to eject electrons, just as whole atoms were in the evaporation of liquid.

However, in the photoeffect there were some rather unexpected and rather curious effects observed. For instance, there was a certain characteristic frequency for any particular metal below which no emission of electrons would occur, no matter how intense the light source was - no matter how much light energy was pumped in. Above that frequency the kinetic energy of the electron is directly related to the frequency of the incident light, and nothing else, such as the intensity of the light, or total light energy pumped into the metal. All this is contrary to what we would expect. This should be a simple heating problem; the more heat you pump in, the more electrons should be evaporated, and there should also be faster evaporated electrons around.

This independence of electron ejection to light intensity also shows itself up in the fact that above the ejection threshold, electrons are always emitted, no matter how weak the illuminating source is.

Let's think about the low intensity photoemission for a moment. Imagine that our "metal" surface consists of four electrons bound by their potential wells into the metal. Let's briefly shine some light onto the metal, so that we inject a certain amount of total energy into it.

This energy should raise the temperature of the atom by a small amount. As we have drawn it this would be ¼ of the total injected energy, which isn't enough to allow any of the electrons to be ejected. The only way an electron can be ejected is if all the energy from the light is concentrated in one electron, which then becomes unbound.

Now this can happen for our four electrons either if all the energy is delivered to a single electron in the first place, or if the energy happens to end up in one electron after a series of collisions which drains all the other electrons of their kinetic energy. Now this second process could conceivably happen for our four electrons even though it is rather unlikely, but in a real metal, with millions on millions of atoms and electrons, the chances of this happening are so small that we can completely ignore them. Nevertheless the ejection of electrons is experimentally observed. For the right frequencies, even the most minute amount of irradiation will cause electrons to be ejected. What must be happening is that the energy is being deposited instantaneously in a single electron. If it doesn't happen instantaneously, the electron will have "leaked" away its extra energy before it can get enough to escape, and it must be in one place, or no single electron would get enough energy in the first place to be ejected. The only way we can explain the fact that electrons are ejected even for the lowest intensities of incident light is if the energy is not distributed uniformly throughout space, but at a single point and that it arrives at the metal not continuously, but at definite, discreet times. This is the only way we can accumulate enough energy in one spot, at one time to eject an electron.

The only way we can explain the threshold effects for the electron ejection and the observed electron energy - light frequency relation is if the energy brought on by the light to the one place at the one time is directly proportional to the frequency, and that the proportionality constant is h - the same constant that Planck proposed for the solution of the UV catastrophe!

$$E = L\nu$$

This experiment, if we are to believe the results - which we must - is telling us that electromagnetic waves behave like particles; they carry energy not spread out uniformly in space and time, but localized to certain places at specific times, and really this is all that a particle is - something that is in a certain place at a certain time!