Introductory Quantum Chemistry

Prof. K. L. Sebastian
Department of Inorganic and Physical Chemistry
Indian Institute of Science, Bangalore

Lecture - 1
Wave Particle Duality

Ok well. Let me start by wishing you all a very good morning. Well, you see there the lectures are going to be on introductory quantum chemistry of third year B S C and first year in M S C level. And, this of course, is my address and affiliation there on the screen. Well, before I will start my lectures; I would like to acknowledge a few people; this is my own department at the Indian institute of science Bangalore, one of the oldest departments of chemistry in the country. And, of course, I am here because of professor Mangala sunder, I actually should have given this lectures in Bangalore, but; it is better to come here I thought. So, Mangala sunder then of course, NPTEL and then as I proceed you will see that I have taken material from Tintin comics YouTube, this website and several other websites. I mean; I have as far as possible I have tried to acknowledge them. If any acknowledgment is missing, if I may be point it out to me and then I shall try to put in the rough censes.

So, the first 3 or 4 lectures will be very introductory it will hardly use any mathematics. But; it will give you an idea of why quantum mechanics is strange? And, at the same time absolutely beautiful. So, that is the aim of the first 3, 4 lectures. In fact, when a student, particularly a student of chemistry and counts its quantum mechanics; it is a rather frightening thing people or students are not too happy with it. And, many times teachers also not too happy with it. And, so it is to say; suppose to be a very frightening thing something like the next picture. That you are going to see.

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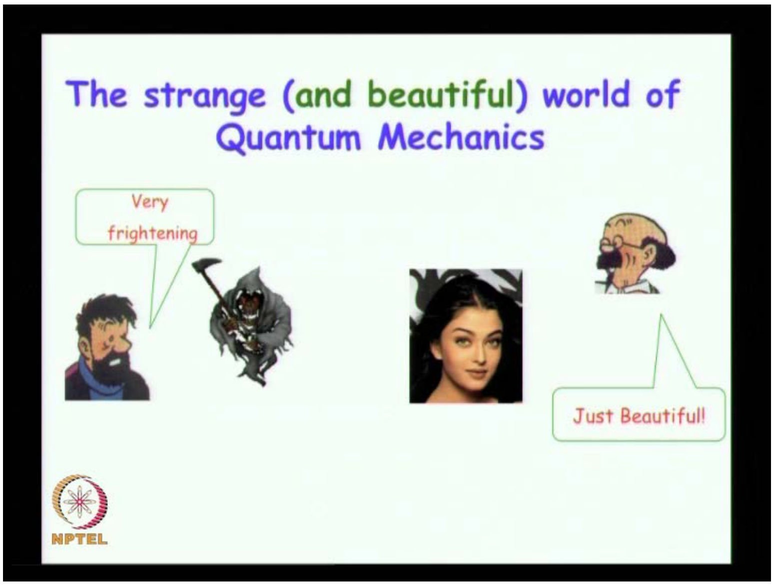

This is essentially because; you see one looks at them mathematics one does not try to understand the physics, the physical situation. But if you try to understand the physical situation and then understand the mathematics things become much better. In fact, it is a very beautiful subject, quite nice and beautiful. One of the most beautiful subject ever developed by human beings. In fact, I would say that; it is much more beautiful than the next picture. That you are going to see of course, I may never say that is my personal opinion that is my personal opinion.

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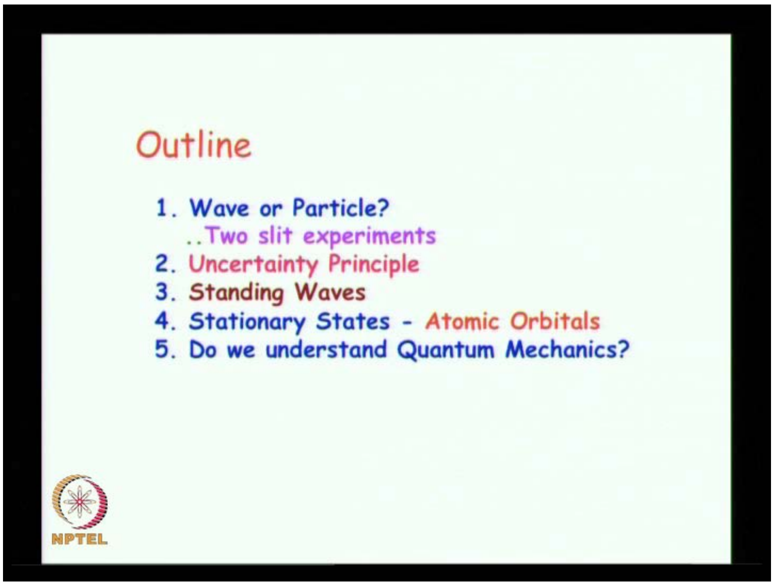

So, here is an outline of what I am going to describe in the first few lectures. The, I shall start with this question; wave or particle. I am sure you would have heard about this microscopic things like; the electron or the proton or the neutron any of these things have a dual nature. They have a particle nature as well as wave nature. So, I shall try to illustrate that; I shall try to make the ideas clear by describing what are ((Refer Time: 03:52) to us 2 split experiments? And, then I shall talk a little bit. I mean, we will discuss on certain difference slit mod it here later, but; I shall talk a little bit about the uncertainty principle. And, then go to what are known as standing waves? Then talk about stationary states and the atomic Orbitals. And, ask this very interesting question do we understand quantum mechanics? Right, I am sure you would be surprised by this kind of question at this point.

Then I shall talk about an approach; which is not usually used by chemist it is known as the approach. In fact, again in my opinion it is one of the most beautiful things. And, to be discussed its connection with the random work. So, this is an outline of the first 3 or may be 4 lectures. So, what about 2 slit experiments? Well, to do as 2 slit experiment well, you see what we will do is; we will imagine that the 2 slit experiment is done. First we will imagine that it is done with the particles. And, I am sure all of you will agree that bullets are particles, we have absolutely no doubt that bullets are particles.

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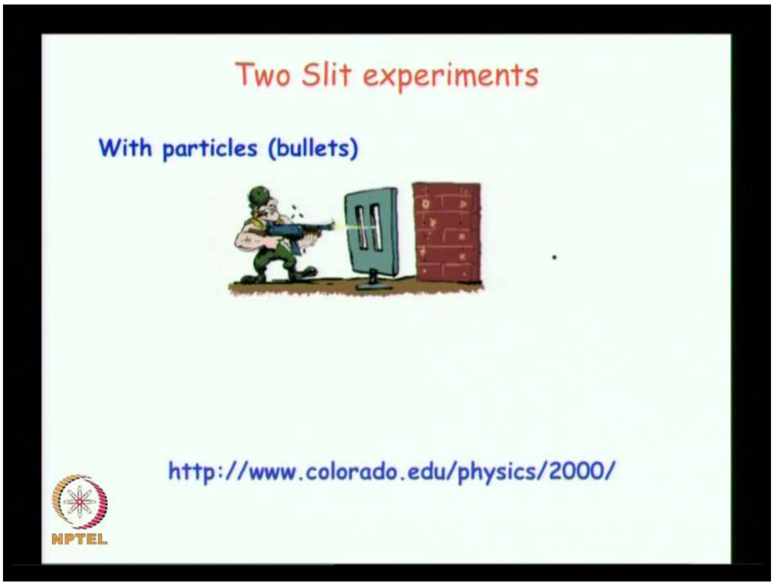

So, I shall imagine; of course, this is a hypothetical experiment nobody who is in the right sense will ever do this experiments and without doing the experiments. You know exactly what is going to happen. Then, so we will imagine that this is first done with particles. And, then we will think of what happens if the same experiment is done with waves? There of course, you have to do the experiments to get the results. And, then finally, we will ask; what will happen if you do this experiment with electrons over other microscopic things. And, the answers are very interesting. So, let us imagine that we are going to do this experiment with particles, in facts bullets.

If you want to do 2 slit experiments with bullets then; obviously, you have to have a sort of particles which in this case of course, would be a gun. So, you imagine that you have a person who has having a gun and there are 2 slits. Here, are the 2 slits and this person with who is guiding the gun, he is going to shoot out bullets just to make things interesting. You can imagine that he is drunk. So, he is going to shoot out bullets in random directions. And, you have these 2 slits; what is going to happen is that; only some of the bullets will be passing through the 2 slits. And, whenever a bullets passes through a slit what is going to happen? It is going to be inserted upon this wall here, which I am going to refer to as the back stove. And, whenever a bullet hits the back stove, it is going to leave a mark on this back stove. And, as I said this is imaginary experiments designed or thought experiments rather than to say and you can.

So, therefore because; it is a thought experiment I can imagine that is given may be 100 1000 bullets you shoot out all of them, may be 5000 of them will pass through this 2 slits. And, will be hitting the back stove. And, so after he has done this, what will I do? As a scientist, I will go look at the marks that have been made by the bullets at the back stove. And, plot a graph I mean; that is what a scientist would normally do. And, plot a graph which shows how these marks are distributed on the back stove. And, I shall refer this as an intensity distribution for the bullets. So, if you did that what would be the results? There he is shooting out the bullets. And, in fact, this figure is taken from that particular website.

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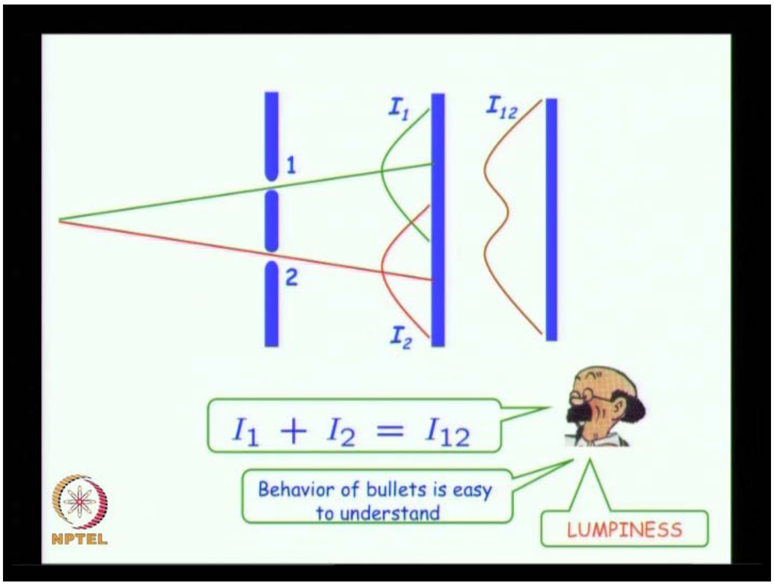

So, here is the schematic arrangement of the results that you will obtain there are these 2 slits. And, I am going to imagine that only this slit; that is this slit number 1 is kept open while the other slit is kept closed. And, so what is going to happen is that; any bullet that reaches the back stove would have passed through the slit number 1. And, most of them what is going to happen is that; they will arrive somewhere in this locations where, in the vicinity of that point. But it is also possible that a bullet might hit an edge at this location and be deflected and perhaps once in a while a bullet may arrive that location also because of deflections.

So, as you plot the intensity; what are you going to get? You will get a curve which has a maximum like the 1 that shown in the figure. And, as you go away from the maximum, the intensity wave will decrease. And, I am going to refer to this intensity distribution as I 1. Why the subscript1? Because; I am keeping only slit number 1 open. So, suppose instead of doing this I had kept only slit number 2 open, what would be the result? This curve shown with the red color would be the result. And, I have called it I 2.

Now, suppose you would do an experiment where, both the slits are over kept opened. Then what is the result? I mean you do not have to do this experiment to say what the result will be. At any point bullets will be arriving, they might have passed through slit number 1 or they might have passed through slit number 2. If they pass through slit number 1 the intensity distribution is I 1. While, if they pass through slit number 2 intensity distribution is I 2. So, I 1 2 right, the intensity distribution in the case where both the slits are open, I will inward the symbol I 1 2. And, if I wanted to calculate it what should I do? I would have to take the sum of I 1, and I 2. So, I 1 2; obviously, will be the sum of I 1 and I 2. And, that is simple and straight forward.

And, not only that you see the bullets have another very interesting characteristic, you see; I will always be getting 1 bullets or 2 bullets or 3 bullets 4 bullets and so on. I do not ever get fraction right, I do not get fraction. So, see the bullets have something which may be referred to us as lumpiness. Right, If I am doing an experiment, I would have 100 bullets or the next possible number of bullets is only 102, I do not have 101.5. I would have 100 bullets 101 and 102 and 103 and so on. So, bullets are what I may refer to as lumpiness that is a characteristic of particles ok.

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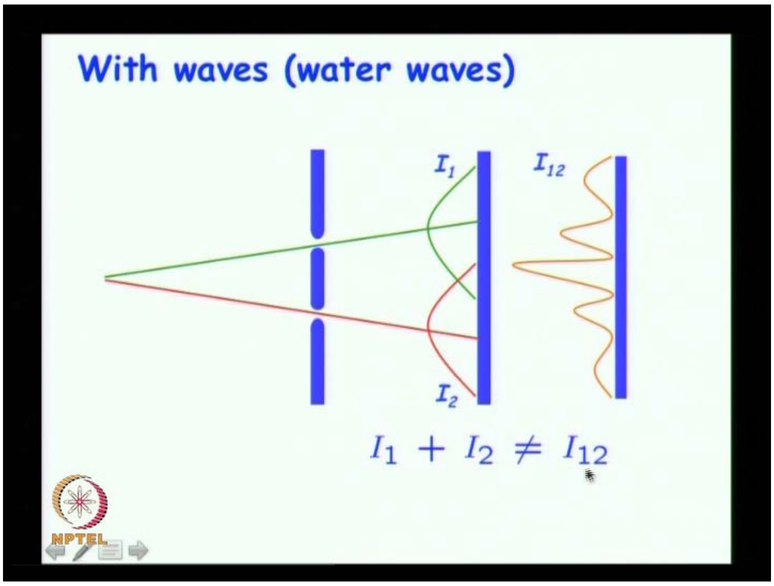

Now, suppose I did the same kind of experiments with waves. This experiments you can actually perform, how would you perform it? You could imagine it that; you have a large trap of water here, and I will have something that is vibrating right, something that goes up and down on the surface of the water. May be a pencil or something attached, when electromechanical device. The device causes; the pencil to vibrate and thus it vibrates. And, it will penetrate; it cuts the surface of water. So, that is my source of waves and then here, I will have wall which will cut the surface of water or a board or something will cut the surface of water. And, on that I am going to 2 slates. So, that the waves that are produced there can pass through these 2 slates and be detected on the other side.

So, that is the experimental arrangement that you have to imagine. And, what is the result? Well, if you schematically represented you say, you have the 2 slates 1 and 2. If I kept only a slate number 1 upon; what is going to happen? You will get an intensity distribution which may be the represented by this green curve called by the name I 1. And, if you kept only a slate number 2 upon; what you get? You will get this curve red one denoted by the symbol I 2. And, the question is what will happen if you keep both the slates open. In the case of bullets it was clear that; you can get I 1 2 ask sum of I 1and 2. And, is that what you are going to get. Well, this is not the result if you are going to do the experiment with waves. The result that you get is not this, you cannot get I 1 2 by adding up I 1 with I 2. And, the actual intensity distribution that you get has its series of maximum and minimum.

In fact, there are points; for example, a point here or a point there where the intensity distribution is extremely low close to 0, but; there are also a points here or there perhaps where the intensity is somewhat large. So, get a series of maxima and minima and you I am sure you will know the reason for this. This is essentially because; waves exhibit the phenomenon of interference. Here, waves exhibits the phenomenon of interference and that is the reason why this happens. I shall explain this in little bit more detail.

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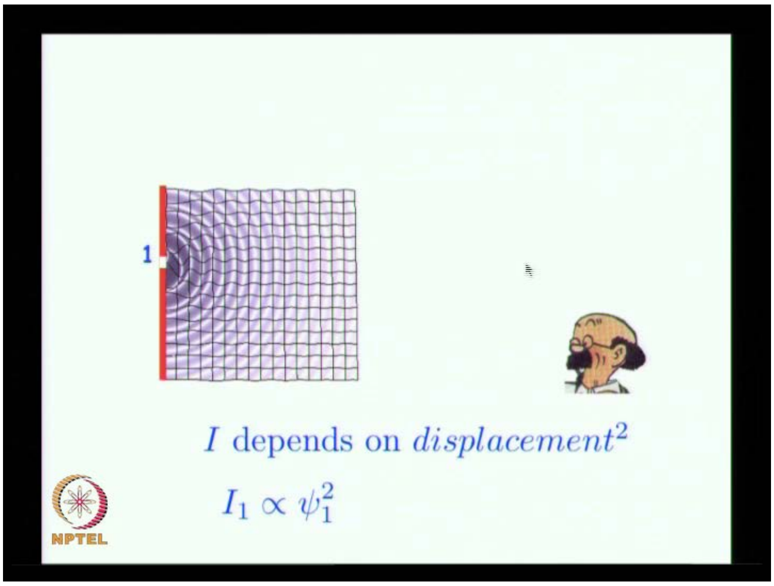

So, it is obvious that; if I wanted I 1 2, I cannot get it by adding up I 1 with I 2. And, the question is how will I get I 1 2? If I want it to calculate I 1 2, what is the thing that I should do? Well, let us imagine that I have only one slit open. And, in such a situation what is the result? Well, I have kept only one slit open and you can see that the waves are coming out through these split and they are spreading. And, suppose I am sitting here, and trying to look at the waves. Then I will find that there is some intensity, for those waves at that point. And, if I want it to calculate the intensity, when I am not going to go into details of waves and splits, but; if I want to calculate the intensity roughly; you can say well, intensity is actually dependent upon the displacements of the water surface at that point.

But, displacement as sooner can be in the upward or in the downward direction. So, what would you expect? You would expect that the intensity has to be dependent upon I mean; it has to dependent upon the square of the displacement of the water surface at that point. As I said, I am now going to giving you all the details. But roughly speaking it has to be proportional to the, it has to depend upon the displacement square. It has to be a quadratic involving displacement. So, therefore; you see if I have only split number 1 upon, what should I do? At any particular point, may be a point here, what I will have to do is; I will have to look at the displacement and I will have to think of calculating the intensity using this coir of something that is quadratic and the displacement.

And, that displacement I am going to denote in this displacement naturally would expect that it should be called d. I am going to give a notation, but; just for the sake of convenience I am going to call it psi. Because essentially psi eventually psi is going to come into discussions. So, therefore, what will happen is that I will say I 1 why should I put the substitute I 1 because; only split number 1 is open. And, if I want it to calculate the value of I 1, what should I do? I will have to find the displacement in any particular point and take its square and calculate its square essentially. I mean; do something with psi square essentially, I shall get the intensity. As I said this is not complete description, but; this is enough for a purpose.

Suppose instead of keeping only split number 1 upon, suppose you have kept split number 2 open. What will be the result? Well, all that will happen is that in particular point there will be a displacement caused by the waves which are passed through the splits. And, that displacement I am going to call it psi 2. And, naturally the density I 2 will be dependent upon psi 2 square ok.

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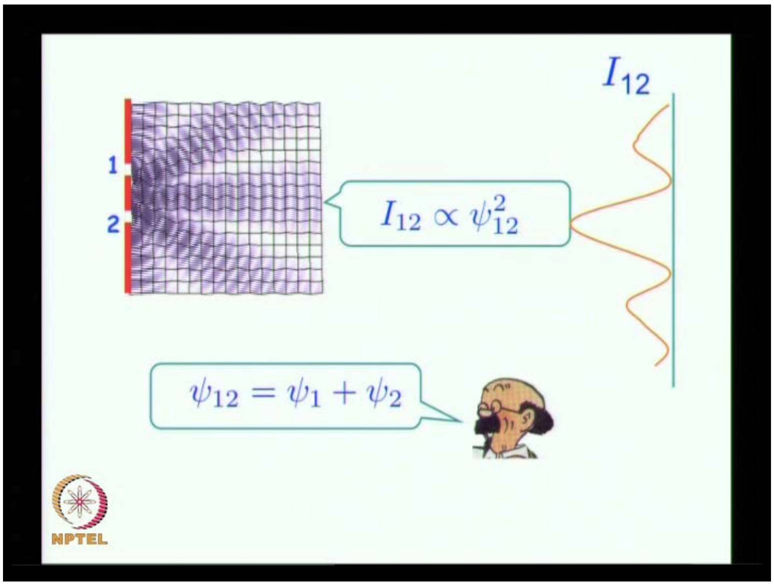

And, now suppose I keep both the splits open right. What is going to happen? Well, if you kept both the slits open, this is how the displacement would be. If plotted the displacement as a function of position, this is how it is going to be. You can see that; say for example, some where here, it is hardly any displacement. While somewhere there, you will see that there is large displacement right. Why is it so? The answer is actually extreme simple, I have kept the both the slits open, the waves can pass through both the slits. And, at any point what is happening is that; there are waves which are passed slit number 1 and arriving there. And, there are also waves which are passed slits number 2 and arriving there.

And, the net displacement at this location will be due to these 2 waves. And, the displacement due to the first one is psi 1, displacement due to second one let us say it is psi 2. And, what will be the total displacement? Total displacement has to be sum of these 2. Therefore, we have this equation which says that psi 1 2 must be the sum of psi 1 and psi 2. And, what can happen is that you see psi 1 psi 2 may both be in the positive direction in which case; you will have a large displacement. While it may happens that psi 1 and psi 2 may be having opposite signs in which case they will cancel each other. And, you will have various mould displacements. That is the reason; why you find that it is in this region, there are in this region or in that region. There is hardly any displacement while in this region; it is a fairly large displacement.

And, therefore; what will happen if you look at the intensity? Intensity as you know is going to be calculated as or it will depend upon the square of psi. So, naturally if the psi has small value intensity also would have a small value. And, that explains how you get this particular interference pattern that we saw earlier. So, this is the pattern that you will get. Now, suppose you did the exactly same experiment with electrons. So, how will you do the experiment; you will imagine that you have an electron gun. So, the electron gun is going to shoot, to give you electrons what you will have to do is; I am not going to the details of the experiments.

But you will have to select electrons all of which have the same energy. And, pass them through an arrangement of 2 slits. And, you will have to detect where they are arriving on a screen. These things can be done these days; there is no problem with that. The only thing is that; you see you cannot do it in this room because; this room has air. If I produce an electron will not go anywhere it will collide with the molecules and it will go up somewhere. So, you have to do this experiment in ultra high vacuum. And, not only that these days you see you have detected which are extremely sensitive they can detect even the arrival of a single electron ok.

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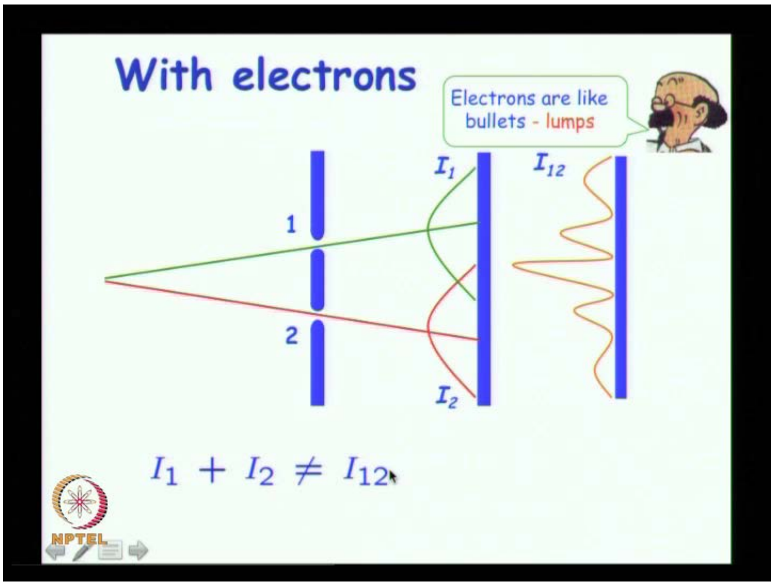

Such an experiment was in fact, done I will give you the details of the experiments in a few minutes. So, what you do is; you say that this is my source of electrons, these are the 2 slits and this is the screen on which I detect the arrival of electrons. If I kept only slit number 1 upon; I will get this energy distribution which I shall refer to as I 1. Well, like if I kept only slit number 2 upon; you will I 2. And, in fact; as I told you it is possible to detect the arrival of electrons one by one. If you want, you can actually see we are arriving as you will see in the video which I am going to show you. And, you find that electrons actually arrive in lumps. You do not get half an electron; you get 1 electron 2 electrons 3 electron 4 electron and so on.

So, therefore in that sense electrons are actually some bullets and bullets are particles right. So, they seem to be similar bullets. And, therefore; if I use that and ask the question what will be I 1 2? I 1 2 is the intensity distribution in the case where I keep both the slits open. And, what would be the expression for I 1 2 and what would be the answer; obviously, it has to be the sum of I 1 and I 2, it has to be. So, the expectation is that I 1 2 must be the sum of I 1 and I 2, but; if you actually do the experiment, you do not get the result to be this is sum. But what I get is actually, an interference pattern. See even though, the electrons are like bullets and they are, in that they arrive in lumps. The intensity distribution that you experimentally find is not characteristic of particles, but; it is characteristic of waves which exhibit interference phenomenon. So, in this case I 1plus I 2 is not equal to I 1 2.

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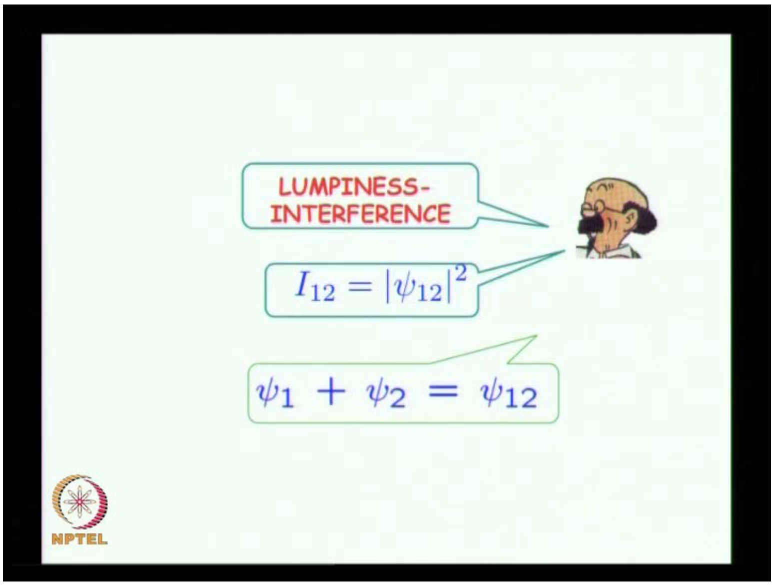

But suppose I wanted to calculate I 1 2, what should I do? Well, it may say you see; just like we thought of the wave function. So, it is to say wave function in the case of water waves; what was it? It was actually the displacement of the water surface. Just like that; you have to imagine there is something that is associated with electron which we will refer to as the wave functions. And, called by the simple, denote by the simple psi. What is the use of it? Well, the use is that; from it we can calculate the intensity. Number of electrons arriving at a particular location, I can calculate from this psi. And, it so happens that in the case electrons all that you need is you take wave function psi and take its square. And, you will get something that is proportional to the intensity ok.

So, that is something that you will have to assume. In fact, instead of saying that it is proportional I have just said that it is equal to, but; strictly speaking it is proportional. So, I 1 2 is the intensity of electrons arriving at different locations on my. When I say intensity of my electrons it essentially means; numbers of electrons are having per unit area. So, I 1 2; you can calculate from the knowledge of the wave function and it will be well, strictly as of speaking there will be a proportionality constant also. But for the sake you are simplifying the notation I have omitted that; I 1 2 is actually equal to psi 1 2 square. But if you wanted to calculate psi 1 2; what will you do? Just assign the previous case.

What you will have to do is; you will have to say that psi 1 2 has to have 2 contributions 1 coming from things that are passed through slit number 1. And, the other coming from things or wave which are passed through slit number 2. And, therefore; psi 1 2 must be the sum of psi 1 and psi 2. So, what is psi 1? We will say that it is the contribution to the wave function of the electron from the waves which are passed through slit number 1. And, psi 2 again similar thing, contribution from the waves which are passed through slit number 2. And, these 2 contributions I have to add together, I am getting the total wave functions. And, once I get the total wave function; what should I do? I should take its magnitude and square it and I am going to get the intensity ok.

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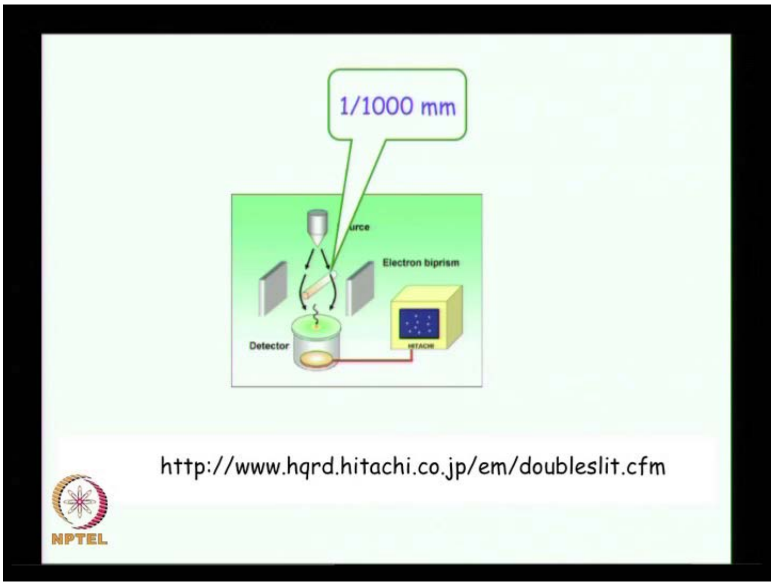

This is the address you where you should have a look at. And, the experiment that was carried out by these people is the one that is shown in this picture. There have a source of electrons which produce the mono energetic electrons; that means, electrons all of the same energy. And, they had a very thin wire here, is the wire it is only 1 by 1000 of a millimeter thick. And, the electrons from the source can pass through the left side of the wire or through the right side of the wire. So, essentially this is over the switch.

And, they are incident upon a detector; this detector is actually capable of detecting the arrival of a single electron this was essentially developed by the Hitachi Company. And, so the experiment was carried out in the Hitachi Company in Japan. So, what I am going to show you is a video taken from their website. And, what you are going to see is the thing that is seen on the screen. On the screen you will find that bright spots appear, these bright spots each one of them is a single electron or a moving at the screen ok.

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Now, we are looking at the detector plane on the monitor. Bright spots appear here and there. These spots indicate individual electrons.

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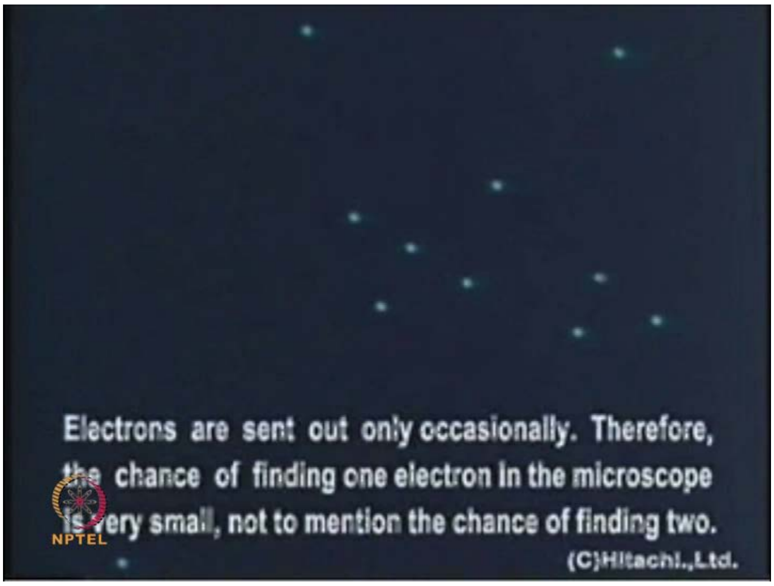

Electrons are sent out only occasionally. Therefore, the chance of finding one electron in the microscope is very small, not to mention the chance of finding two.

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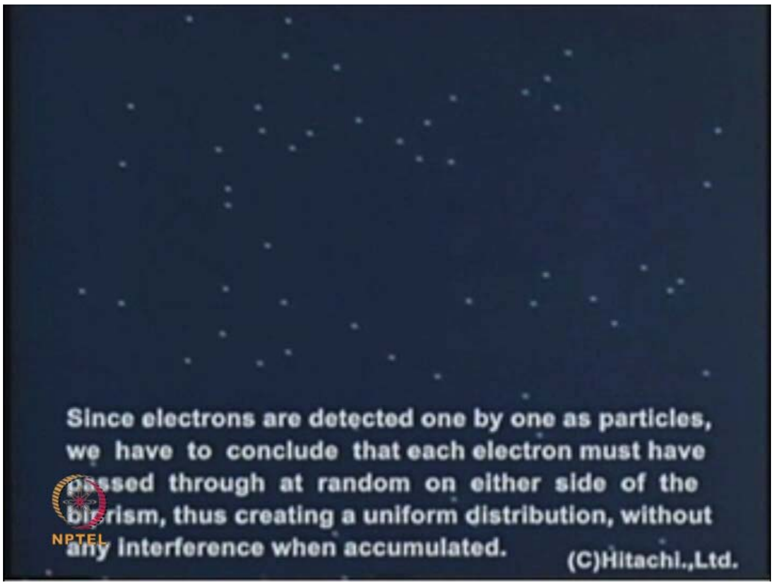

Since electrons are detected 1 by 1 as particles, we have to conclude that each electron must have passed through at random on either side of the biprism, thus creating a uniform distribution, without any interference when accumulated.

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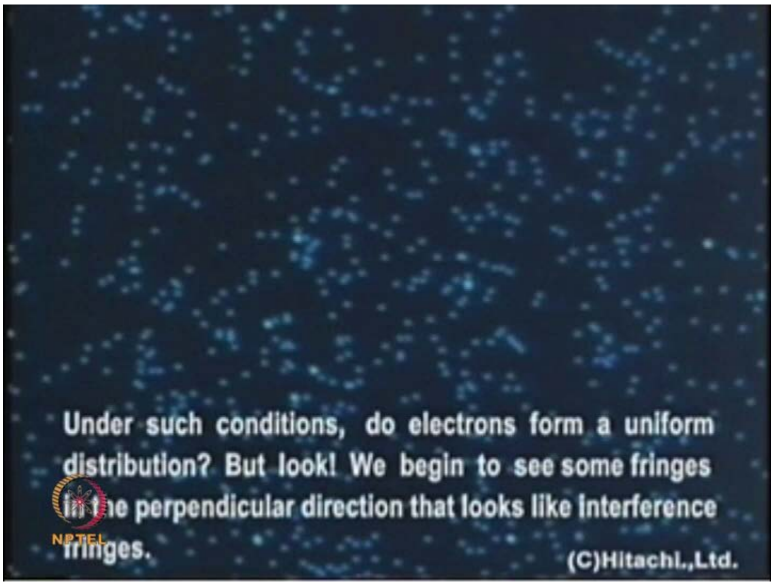

Under such conditions, do electrons form a uniform distribution? But look, we begin to see look some fringes in the perpendicular direction that looks like interference fringes.

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Since this experiment lasted for more than 30 minutes, I have sped the move up. Interference fringes are now clearly visible. So, therefore; you have seen the video and you can see that this better from an actual experiments. The interference patterns are clearly visible and this indicates that electrons do have a wave associated with the mould. So, it has shown you that electrons arrive one by one and therefore, they resemble bullets. And, so they have to be referred to as particles, but; these are particles which also have a wave nature.

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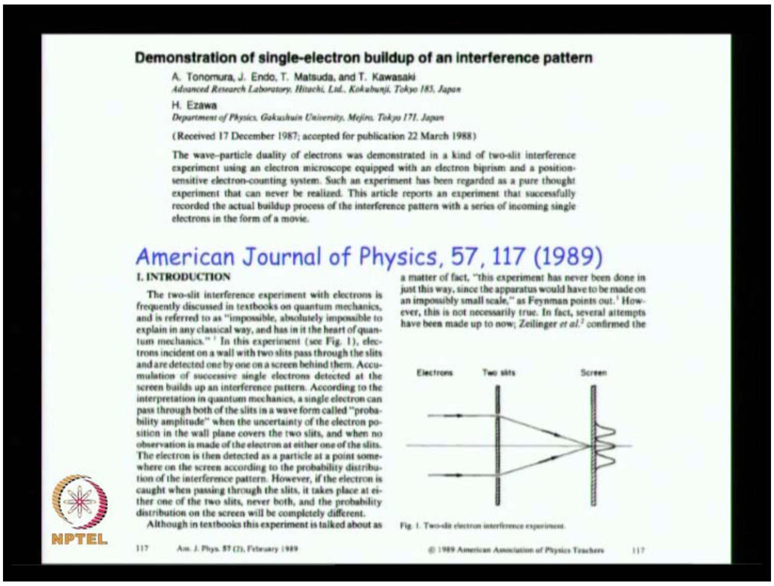

Demonstration of single-electron buildup of an interference pattern

A. Tonomura, J. Endo, T. Matsuda, and T. Kawasaki
Advanced Research Laboratory, Hitachi, Ltd., Kokubunji, Tokyo 185, Japan

H. Ezawa
Department of Physics, Gakushuin University, Mejiro, Tokyo 171, Japan

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The wave-particle duality of electrons was demonstrated in a kind of two-slit interference experiment using an electron microscope equipped with an electron biprism and a position-sensitive electron-counting system. Such an experiment has been regarded as a pure thought experiment that can never be realized. This article reports an experiment that successfully recorded the actual buildup process of the interference pattern with a series of incoming single electrons in the form of a movie.

American Journal of Physics, 57, 117 (1989)

I. INTRODUCTION

The two-slit interference experiment with electrons is frequently discussed in textbooks on quantum mechanics, and is referred to as "impossible, absolutely impossible to explain in any classical way, and has in it the heart of quantum mechanics."[1] In this experiment (see Fig. 1), electrons incident on a wall with two slits pass through the slits and are detected one by one on a screen behind them. Accumulation of successive single electrons detected at the screen builds up an interference pattern. According to the interpretation in quantum mechanics, a single electron can pass through both of the slits in a wave form called "probability amplitude" when the uncertainty of the electron position in the wall plane covers the two slits, and when no observation is made of the electron at either one of the slits. The electron is then detected as a particle at a point somewhere on the screen according to the probability distribution of the interference pattern. However, if the electron is caught when passing through the slits, it takes place at either one of the two slits, never both, and the probability distribution on the screen will be completely different.

Although in textbooks this experiment is talked about as a matter of fact, "this experiment has never been done in just this way, since the apparatus would have to be made on an impossibly small scale," as Feynman points out.[1] However, this is not necessarily true. In fact, several attempts have been made up to now; Zeilinger *et al.*[2] confirmed the

Electrons Two slits Screen

Fig. 1. Two-slit electron interference experiment.

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So, this is the actual paper in which these, that was published; it is a great interest to anybody who is interested in physics particularly quantum physics. In fact, somebody has put together a list of 10 most interesting experiments ever carried out in physics. The list was prepared and I think this is actually either number 1 or number 2 in that list. So, this is considered to be among the most interesting experiments carried out by physicist. And, that is the exact reference, but; then you see you have to notice something happened in the video. See the electrons were actually sent out from the gun under identical conditions right.

They were all prepared in the same fashion and they were all coming out of the gun. But then when you look at the video screen; what has happened is that; they are arriving at different locations. Right, this seems to violate the basic ideas of doing experiments. You see, if you do an experiment you would expect that the result is will always be the same. And, this does not seem to be happening in this particular experiment, because; if send out 1 electron it may arrive somewhere here at the detected. But the next time the electron is arriving somewhere there. The third time the electron is some arriving somewhere else.

Right, this is as if you are in the chemistry lab doing it titration the first time you do the titration you get an answer may be 15, next time you do the experiment you get an answer of 22.1 and the third time you do, you get 30.2 and then you would think that ok. This is not the way the answer the basic idea of science that experiments created again and again should give you the same answer. But here, what happens is that when you sent out 1 electron you cannot say exactly where it is going be, you can only talk of the probability. Say for example, you have bright regions and there you can say there is a large probability that the electron will arrive there. You also had dark region there you can say the probability of finding them is small.

So, here it seems that you can make only probabilistic statements not exact statements. So, then you will ask then what sense is this particular experiment reproducible, the answer is the following. Suppose, you had sent out may be 100 1000 electrons and collected the pattern. Then you will get the interference pattern. If somebody else, somewhere else in the world does these same experiments with 100 1000 electrons and gets the patterns. Then your pattern and his pattern will be identical. So, therefore; the experiment is reproducible in that sense. But if you are sending out only 1 electron you cannot actually say where it is going to arrive. So, you can only talk of the probability will arrive at the regular location that you can talk about.

And, if you wanted to calculate the probability of what is the procedure, that you can adopt the answer that you have to go back your wave function. If you actually wanted to find the probability; you will have to calculate, you find the wave function and you will; obviously, be able to find. To say, that the probability should proportional to the square of this wave function. Earlier we were saying intensity is proportional to the square of the wave function. We modify that slightly because; we are now thinking of a single electron. And, if I am sending out a single electron I can say my wave function is going to give me something which is proportional to the probability that is actually size square. The wave function square will be proportional to the probability of arriving at a particular location. Now, there were great scientists who were very unhappy with this. You see they thought that; if I send out the single electron it should be possible for me to say exactly where it arrives, but; quantum mechanics does not do that.

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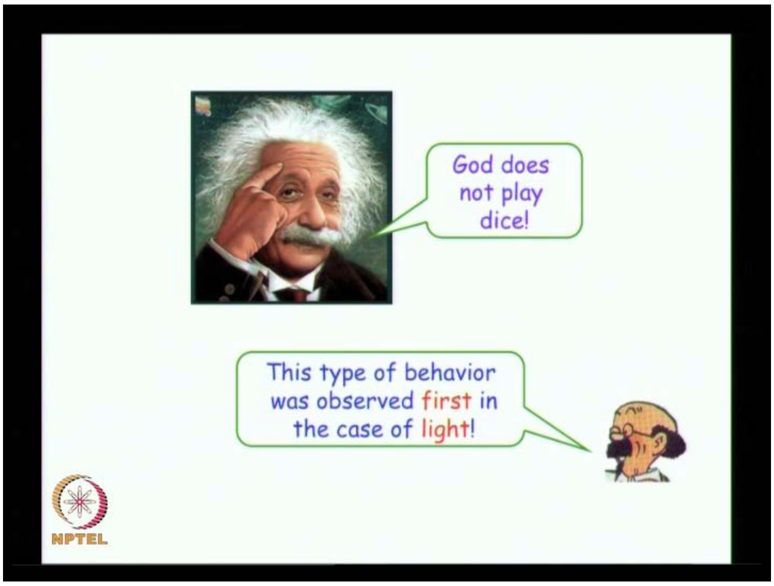

So, scientists like Einstein were very unhappy about it. In fact, Einstein made a very famous statement. He said that you see the behavior of an electron is described in quantum mechanics is not completely satisfactory. Because; you know if I added dice, if I toss it and the answer can be any one of the numbers 1 to 6. And, nobody can say prior a priory what would be the answer will be. We can only talk of the probability that the answer is a 5or a 6 or a 4 and so on. And, you see it in the cases of a single electron; if you are sending out a single electron, you are talking only of the probability that there electron will arrive at different locations and that cannot be correct.

And, therefore; he made this very famous statement which is reproduced here. God does not play the game of dice. By which what he meant was that he does not believe in the description of nature using quantum mechanics without that it was not complete. But what our experimental evidence we have till today; indicates that this universe obeys quantum mechanics and it seems that god does play the game of dice. And, again historically speaking this kind of behavior was actually first of served in the case of light.

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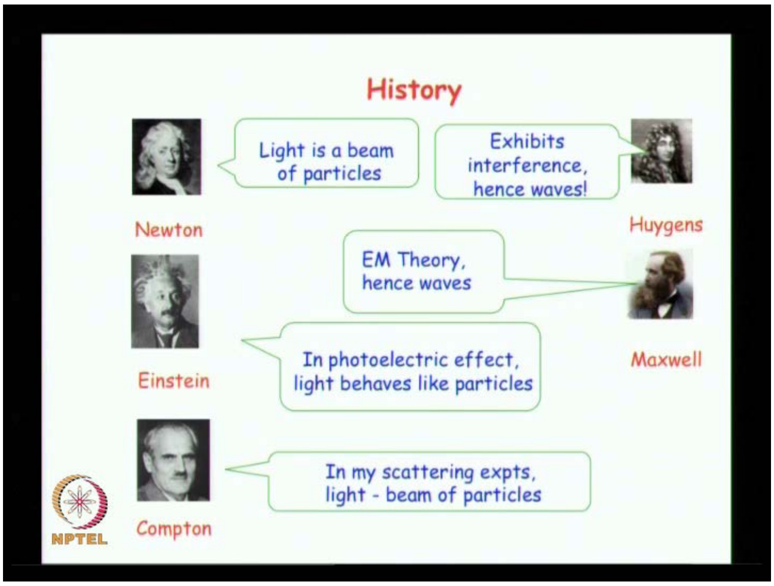

So, by this what I mean is this experiment regarding wave particle divided your dual nature of microscopic things was first served in the case of light. So, this is a little bit of historian not too much detail. This is actually Newton and he was among the first to propose a theory of light; what he said was that light is a beam of particles, this was his suggestion. Even though, before him Huygens suggested that light exhibits interference and therefore, you have to think of it as waves. But you see; Newton was much more well known than Huygens. And, because; he was so much more famous, people simply accepted what Newton said and they discarded the wave theory of Huygens. But then later on what happened was Maxwell came along he formulated what is known as the electromagnetic theory of light according to which light does a wave nature. And, this was accepted it could explain.

So, many experimental phenomenon therefore, the theory of Maxwell was accepted until Einstein came along. And, he said that in order to explain the phenomenon of photoelectric effect; the experimental observations in photoelectric effect you have to assume that light has a particle nature. So, all the experimental observations regarding the photoelectric effect could be explained. Assuming that light has a particle nature, it is the beam of particles. But even though, Einstein made the suggestion nobody believed him. This suggestion was made in 1909. So, in 1905 and there is this person (Refer Time: 36:20) who won the noble prize he did not believe in the suggestion of Einstein. And, he wanted to dispose them and therefore, into a series of careful experiments in photoelectric effects. And, the surprise he found was whatever Einstein had suggested was completely correct.

So, then came along Compton and he did scattering experiments in which x rays were scattered from a piece of metal. And, there was a change in the wave length cost by the scattering. And, he could explain this by assuming that; this scattering process is nothing but the collision similar to collision between 2 billiard bolts. You can imagine you have the particles of light which we never refer to as the photon; they collide with the electrons of the metals, something like the collisions between the 2 particles. And, all the experiments could be explained using the particle picture. But then of course, it is also known that light exhibits the phenomenon of interference. And, therefore; it has the wave nature and therefore, scientist were very puzzled.

So, they were puzzled because; you see it is appeared them this is only a joke at appeared to them that on Monday’s Wednesday’s and Friday’s light seemed to behave like a particle. While, on Tuesday’s Thursday’s and Saturday’s it seemed to be behaving like a wave.

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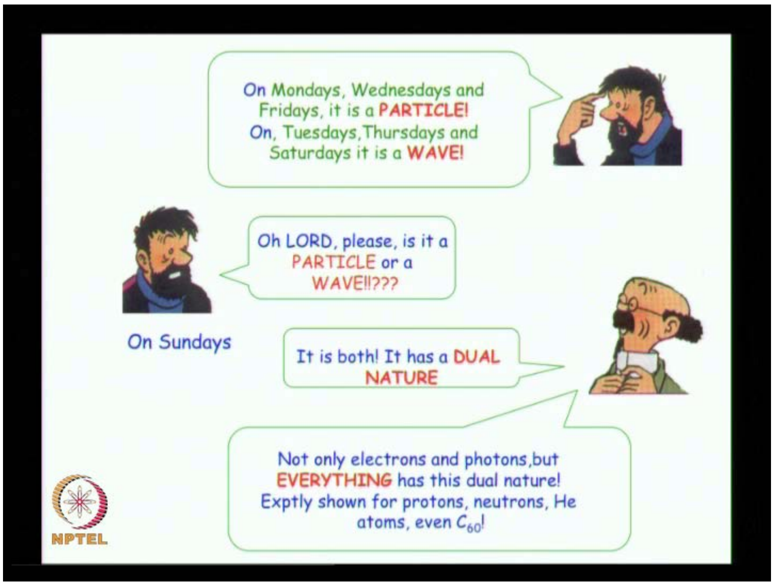

And, naturally if you, if that is the way; it is you have the question what about on Sunday's? Well, scientist of those days; as I said it is only a joke; scientist of those days would go to their place of worship and perhaps pray to go to a clarification whether this is a particle or a wave. But now, it is clear to us actually, it is quite well established that light has a dual nature, not only light it appears as if everything there in this universe as a dual nature. Like even electrons, neutrons, protons, helium atoms, C 60 which is a rather big molecule this also has been demonstrated to have a wave nature.

So, people having trying to show this wave nature experimentally for different particles they have succeed for electrons, neutrons, protons, even for bigger systems like C 60. But of course, you see we do not have for much bigger systems. If somebody says that I have wave nature, I mean; being a big particle you can say I would probably have expected to have a wave nature. There is absolutely no experimental evidence for that. Though, we would like to extra then say that even bigger objects have a wave nature.

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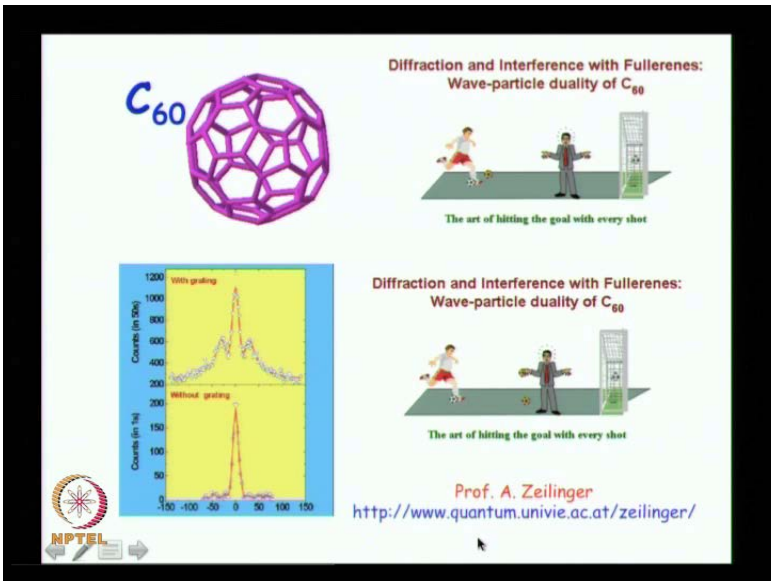

So, this is C 60 molecule, nice foot boll shaped object. And, I want to show you experimental data taken from the group of A. Zeilinger his name you will see in a second. So, you can see the interference pattern that he found here. You can see this pattern which is just interference pattern. And, this is obtained using a beam of C 60 molecules; he made a beam of monolithic C 60 molecules pass them through to a slits. And, then observed this the experiments this interference pattern. Showing that even, a C 60 molecule has a wave associated with it. These are pictures taken from this website. You should have a look at this website; whose address is given here.

Now, though few words about this 2 pictures actually, he this is again another joke; these 2 pictures. Suppose you are playing football and imagine that the ball has a wave nature. Then what will happen? Right, I mean the wave has the ball has a wave nature and let us imagine the wave length is rather large suppose, that is not the actual way it is. Then suppose you see I am standing here, I am the goalie and one of you is going to stand there and it is a kick penalty. So, therefore; you are going to shoot the ball. Suppose you shoot it directly at me, in our classical way what will happen is that; if you shoot it directly at me and if I do not move I mean; obviously, it will not be a goal.

Because the ball will hit me and it will go off somewhere else. But if the wave the football had a wave nature, what is going to happen is that the wave associated with the football can go through this side of me or through the other side of me and right exactly at my back, what will happen? It will be constructive interference. It is actually, at my back. So, therefore; even though I am standing, obstructing it directly goes and it can be a goal. Right, of course, this will not happen; if you would do not have a wave nature associated with the ball. Which, you do not have our real world, I mean; the wave length thus associated with the ball in our real world we would expect it is very small and before you do not see any interference effects.

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Well, as I said people have been doing experiments they have been able to demonstrate wave nature for bigger and bigger systems. What I have here is a; report that 2 or 3 months ago I suggest that people should have a look at this paper, published in nature nanotechnology. The reference is here, the experiment is done with phthalocyanines. So, you are going to see another video now 2 of them.

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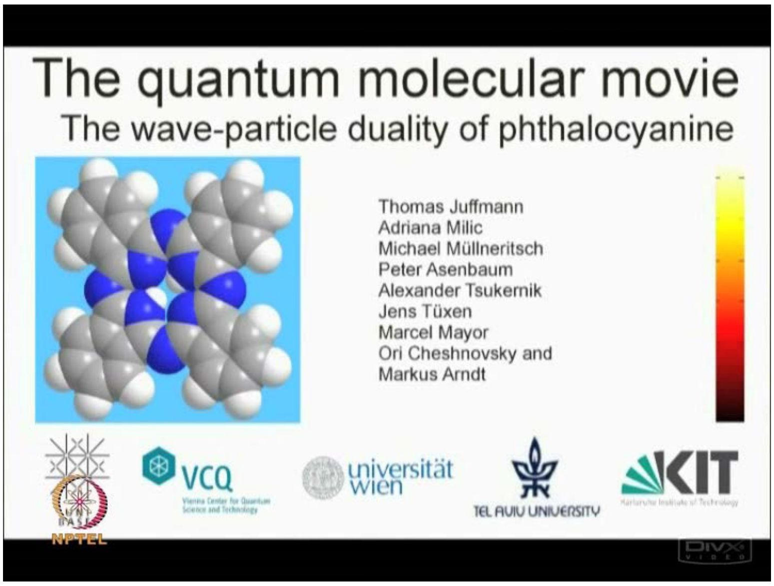

So, this is the molecule phthalocyanine; you can see it. And, these are the single phthalocyanine molecules arriving at the detective screen. The spots; just like the electronic experiment, is bright spots that you see are single phthalocyanine molecules arriving. After having passed through 2 slits. And, you can see the interference pattern that does resettle demonstrating that these also have a wave nature.

So, the interference patterns are very clearly visible. Again, I mean; 1 more video from the same set of people. They are much shorter one which shows the pattern very clearly. Well, this has to be demonstrated that microscopic things have a dual nature they can behave like a particle; they can also behave like a wave. And, we human beings actually we have no direct experience with such things. You see in our world it seems that you see the, if a have a particle it behaves like a particle. It does not behave like a wave.

And, if perhaps waves like waves on the surface of water then there is a way which is particle. For example, there is no lumpiness associated with waves on around the surface of water. So, we have unfortunately no direct experience of things which have this dual nature. And, therefore; we find it very difficult to comprehend. How can the same object behave like a wave as well as a particle? To help you in that direction, I have taken a picture from the web. This has nothing to do with the wave particle duality; it is just a picture that has a dual nature.

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So, if you look at this picture and if we ask you whom do you see in this picture? What would be the answer; well, this picture interestingly has the dual nature. If you are very clever then you can see that there are few people in the picture. But normally, what happens is that people can see only one person. So, where are these two people sitting in the same picture the answer is clear. Suppose, you say that this is the chin of a person that part of the face and that is the mouth and then that is the eye.

Then, obviously; I mean if you imagine that we are then; obviously, this is the picture of an old woman, old lady. On the other hand suppose, you now say imagine this is the chin of a person imagine that is the chin of a person and then this will be the nose that will be the ear and the face of this person is tilted away from you. If you imagine that we are then; obviously, this is the picture of a young girl. And, therefore this is a picture that has a dual nature. As I said this is absolutely nothing to do with wave particle duality; it is just a picture which has a dual nature. So, if you are asked whom do you see in the picture? Then you see; you can say a young girl or perhaps her grandmother. We will I mean the morning the lectures are over.