Optical Spectroscopy and Microscopy
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Lecture – 3
Fundamentals of Optical Measurement and Instrumentation

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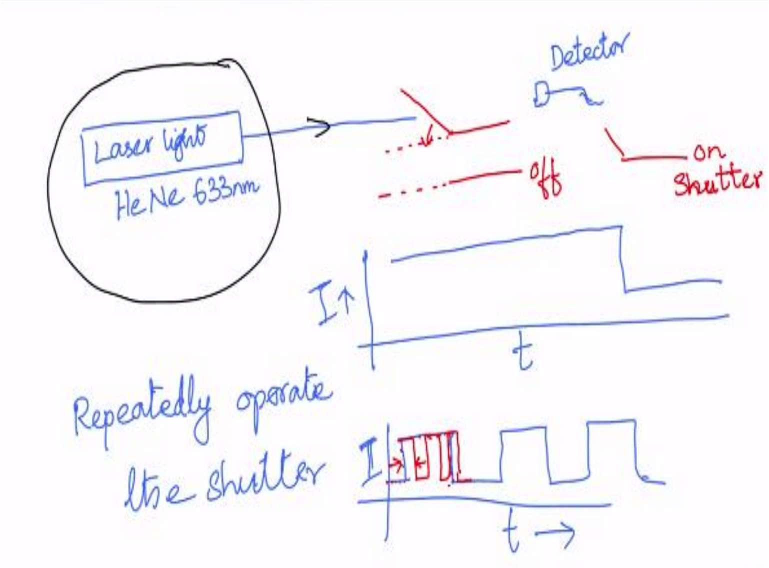

In the last lecture, we were looking at a second kind of a thought experiment where we were taking a laser light source and then putting in a shutter to control the light, the appearance of the light after the shutter and we detected it using a detector. If you take a look at the schematic of the last lecture and then continue that thought experiment, all in the idea of trying to localize the photon in time okay.

Now if we look at the schematic here, what we see is that we have a laser light source, sending in the light and then we have a shutter okay. The shutter exists in 2 states, on state and then off state, and whenever the shutter is off, you have the light coming into the detector, when the shutter is on, there is no light okay. If I plot the intensity of the light as a function of time while I am actually operating the laser, you would expect the light intensity to fluctuate somewhat similar to this.

Similar to the blue line, where somewhat what we would expect is to get this blue lines depending on the lasers turning off and on, right. So now what I was asking or what we were talking about is that this corresponds to the shutter turning on and off with a time period indicated by the blue line. However if I start making the shutter go off and on much more frequently, right, what happens to that? Is there a limit where I start operating the shutter so really really fast beyond which this does not obey?

If it does not obey, what happens to this? It turns out that yes there is a limit, that is if barring mechanical inabilities notwithstanding, suppose we have since this is start experiment, I can actually have a shutter which can operate at any speed. So if you take a shutter that can close on and off really really really fast down to few picoseconds and femtosecond what you will see is that we are turning on the shutter and going off down to let us say microseconds, nanoseconds, and then to picoseconds.

What you will see is that the light will not appear after the shutter after, so even though you are turning off and on, the shutter now will act like a effective light block, it does not let the light pass through, why is that and can we actually estimate at what time, I mean what are the parameters that determine this or that governs this? It turns out the answer is yes and it boils down to the same fundamental mechanical principles that we talked about and the first one being, I mean that the principle first one being the position and the momentum.

We looked at the position on the momentum and then said we can use that to determine what is the localization accuracy for a given photon is, in here we are going to use uncertainty principle in a different form.

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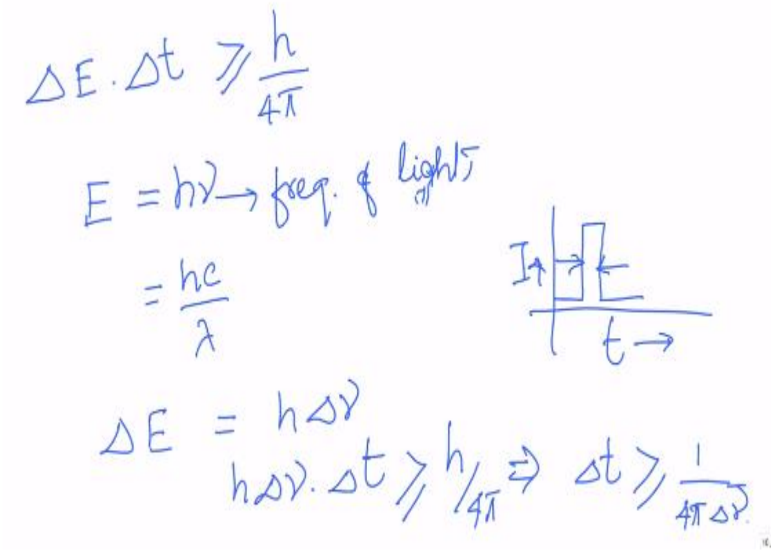

The form that we are going to use is connecting the uncertainty in the measurement of energy delta E with the uncertainty in measurement of time, alright. So these two have to be they are coupled and the product of uncertainty will be greater than our uncertainty principle, the constant h by 4 p. Now what does it mean with respect to the experiment that we just said? We know that the light photons when they are actually coming out from the laser have a definite energy given by each and every photon that is coming out from.

The laser will have an energy given by E = h nu, where nu is your frequency of light of electromagnetic radiation or the light radiation we talked about, okay, and it is convenient to think in terms of lambda, so you can actually recast that into hc by lambda where c is the velocity of the light and lambda is the wavelength of the light. So now this whole expression you could think in terms of the delta E per se, you can think in terms of delta E is h delta nu. As a result if you substitute back into this original expression, what we will have is h delta nu times delta t will be greater than or equal to h by 4 pi.

Now you can see the uncertainty associated with the time, the time localization, right, is very tightly linked to the energy itself and in turn is related to the color of the light. So this in turn can be simplified and then we can write it as delta nu or actually delta t here. We are interested in asking how narrow in time can we localize the photon? Can we measure a given photon being there? Right. So delta t so that is what this means right. Remember the graph that we saw or coming out from the photo detector.

The intensity goes up like this and then comes down. So what you are actually doing is we are actually localizing the photon, this is the intensity here. We are localizing the photon within this time window. So that would correspond to my delta t. What this tells you is that this delta t has a lower limit, I mean it cannot be any lesser than, that is it has to be greater than or equal to, at the most it can be equal to, no h here because h gets canceled, so is equal to 1 by 4 pi delta nu, okay.

If you want to localize it better and better, then you have to give away the ability to tell which color photon that you are actually looking at okay. The delta nu has to go up.

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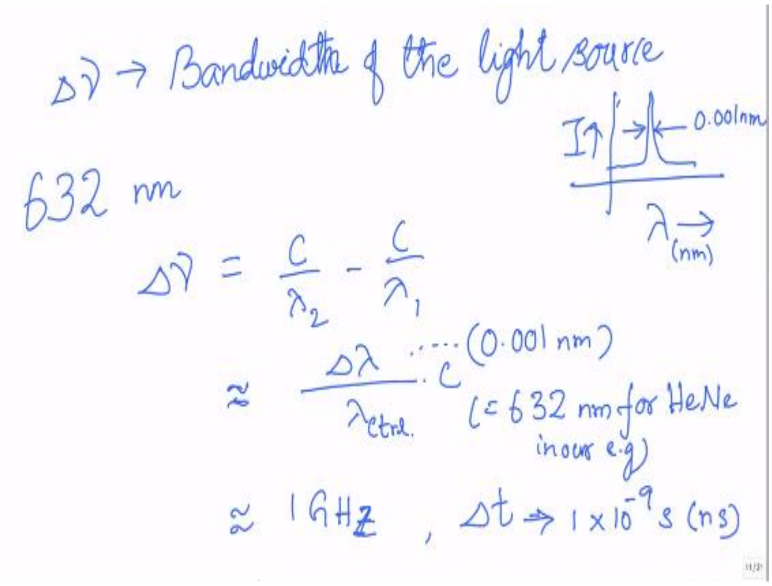

What we call this delta nu as the bandwidth okay of the light source. What it tells you is that, we took the light to be the HeNe helium-neon, right. So let us say if it is a red HeNe 632, that is operating at 632 nanometer, we need to ask how well do we know this 632 nanometer and it turns out this can be pretty narrow, right. If you plot the again intensity versus wavelength here, so wavelength corresponding to the, my wavelength measured in nanometers.

So you will see it is pretty sharp and then the spread that we measure would be we know this pretty accurately to about 1 in 1000 path of the 632 nanometer, let us say to accuracy of about 0.001 nanometer okay. Now please note this is in the units of wavelength lambda and in order to estimate how small time localization can be, we need to express that in terms of delta nu, the frequency, so that is when we have written our expression in terms of frequency, we can also write it in terms of delta lambda, so let us do that first.

So we have delta nu is basically you can write it as C by lambda 2 difference lambda 1. So what we generally tend to do is that we take the central lambda and c and delta lambda, where delta lambda is lambda 2 minus lambda 1. So if we express the central lambda here would be in our example it would be equivalent to 632 nanometer for red helium neon laser in our example okay and the delta lambda is about 0.001 nanometer okay. If you plug these things in and you can go ahead and calculate, and it will turn out to be of the order of about a gigahertz or so, okay.

So this in turn we can actually plug in and then you can estimate the delta t and if you calculate that, that delta t will come down to about 1, again we are talking in terms of the order of magnitude here, this many seconds, so about nanoseconds or so. So you can operate the shutter such that the shutter is on only for about a nanosecond or so until that point, you go to microsecond, you go to hundreds of nanoseconds, until that point you would not feel any effect of this, but once you start operating it down to about a nanosecond are even lesser right, like a picosecond or something.

Assuming that you can actually operate a shutter in that high speed, you would start to see no light coming out of the shuttle if we were to use a helium-neon laser that is having a bandwidth of about 0.001 nanometer, that is 1 in 1000. So if you know it very very few, I mean the wavelength, the color is extremely pure, then your ability to form a short pulse is is limited. I mean we do not see it in a normal life because nanoseconds and picosecond, we do not go down to that in a regular basis.

To just give you a example camera flash that you operate, that is one of the fastest light pulse that you see in a day to day life. The fastest one of late you can if you get buy it in a market is about 1 in 10,000 of a second okay. A regular flash without any extra visions or such it is either you get it at 1 by 60 or 1 by 90 of a second. So compared to that, 10 raise to 9, 10 raise to minus 9 seconds is tremendously low and that is the reason why you do not see it and secondly in a camera flash what you are actually operating on is a white light.

It has a lot of color, so it is a pretty broad spectrum and hence the bandwidth. We will use this very principle to actually when we actually start probing the system at very fine time scale are using high intensities because this is one way of actually generating high intensities and yet keeping the overall photon load to be small is be able to localize the photons in time or can think of that as a time focus. There is a big bust of photons, but only for a very short extremely brief period of time and nothing at all for a long period of time, right.

That is one trick that we can use to minimize the photon load unto the sample which often is a concern, but at the same time, we can probe that with a very high intensity because momentary instantaneous intensities in these situations can be extremely high okay. So if we have to generate a laser light of that kind , then we need to have this in mind and how do we generate them using the lasers and all that we will be seeing in detail in course, but my point here is to say these principles, the quantum mechanics principles are not one of esoteric existence.

It is not like you want to study it you know using a pen and paper and it is really not of much use, it is not of that kind but it is actually very much applicable in the course that we are actually doing and we do use it and in fact quite often you will hear things like okay what is the bandwidth of the laser and what is your spot size of the focus beam that you have focused in the microscope and things like that. For this, the governing principles start from quantum mechanics, that is my point and it is important to understand it not to the greatest detail but sufficient enough for what we need to do it in the course.

So this is all boiling down to one of the ideas that Dirac had put forward which is the absoluteness to the size which led to 2 principles, I mean which led to the uncertainty principle, I kind of led you there and using that I have looked at 2 examples and then shared that how they are very much related. Now the second principle that Dirac has formulated is about superposition of states.

I am talking about this second for quite a good reason because we will be dealing, I mean we will be talking about this using an example and then write after that immediately we will use that in our formulation of obtaining what an expression to describe what happens when light interacts with the matter okay.

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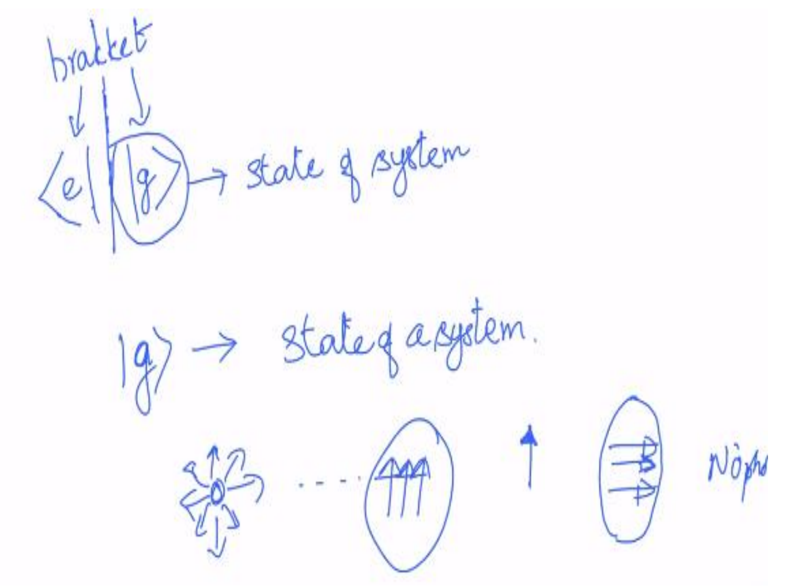

So what is this superposition principle? So, let us look at that. So what Dirac said is that in order to describe matter, we would have to develop a new formalism and in that formalism what he used is that there can be different states the matter or then object or **or** anything that you want to describe can exist. These states are represented by a vector, let us call that, I mean he used a notation called bracket notation, this essentially he took a bracket like that and he split in half and then said basically these form a vector space, ket vector space and the bra vector space.

Each of these vectors would represent a state of a system okay. So in his description, this is what he is going to say, we will give a name, so let us say and this is some g and this is some e of whatever it is. So this for him a or g would represent state of a system, okay. What he realized is that the state of a system have unique properties in that you would be able to use general principles of linear algebra to express various different operations or various different measurements that you can actually make out of the system.

For example if you want to know what is the polarization of a photon that I am actually looking at, okay. So in this example, my measurement process is measuring the polarization itself and then the observable is one of the following which is you would like to collapse them into, so let us say there is a light source okay and this light source passes through filter okay. This represent, these are special kind of filters, let us call them as polarization filters, so I am going to change that into a circular object.

The properties of this filter is such that the photons that are coming out from here once it passes through this filter will be of having a particular polarization okay. I mean that is defined with respect to the axis of this crystal axis. Optical crystal is nothing but any substance that has some unique optical properties, in this case it is actually exhibiting a specific directional property wherein we see that the light photons that are coming out after passing through these filters have defined polarization okay.

What the polarization itself is you can right now think of that as a simple property, but later on, we will see what that could be and all that stuff, so but right now if you do not know what the polarization is, just think of that as an inherent property of a light photon, okay. So given that what we can actually see is that so this polarization is defined with respect to the crystal axis, once you define it with respect to the crystal axis, then what we can actually do is that we can probe or we can ask with a different filter.

Basically rotate this filter to about 90 degree, then the property of the polarization is such that when this direction and this direction are mutually orthogonal, meaning they are different by 90 degree you get no photons at all.

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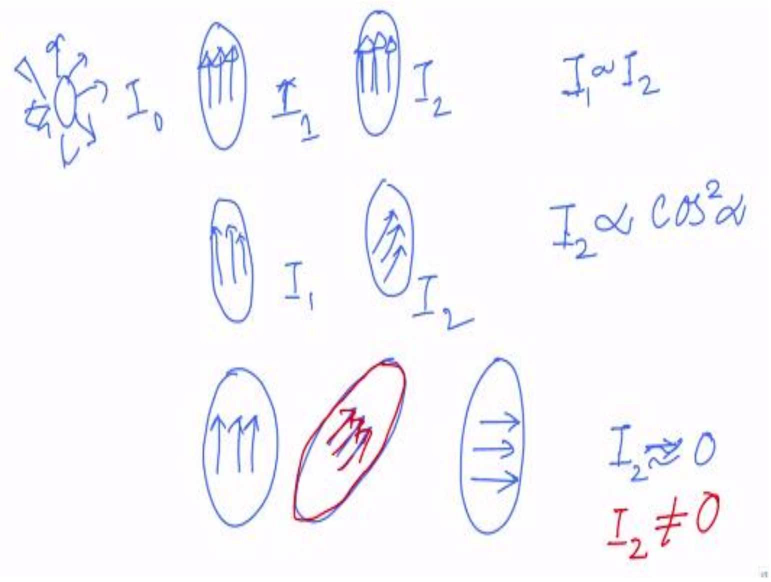

However, if you have the same light source and then we pass it through same filters, now if you had to probe with filter whose orientation is parallel to the original filter, I would get the intensities here and here, right, the I, so let us call this as I input and let us call this as I1 and let us call it as I0. I0, I1, and I2. You will see that the I1 is approximately equal to I2, which is the number of photons coming out from here, I mean there is hardly any change in the photon intensity, albeit some reflection losses and absorption losses, but more or less, you will have the maximum pretty good transmission efficiency of this filters here, okay.

However, if I do this which has so same I1 and then I point my filter at an angle alright, so then the I2 seem to have a definite relationship, even the other one it will explain but I2 seem to have a definite relationship with respect to the I1 which basically is proportional to cos square alpha. Meaning when it is completely aligned, you have I1 almost equal to I2, when completely orthogonal, nothing comes out, but somewhere in between proportional to the angle, proportional to the cos square of that angle, you have this thing, right.

That is, this is a more general statement of the special cases that I have told you, but the cos square representation is more general. So this is no surprising at all, it is pretty simple and one can explain this as just a property of the filter and doing that. However, what becomes perplexing is that let us take a situation where you have the light that went through this polarizer and I have another filter, right, which is like this, and according to our description you would see that there is no light at all coming out, right, I2 would be pretty close to 0, right.

Now if I were to add another filter here okay, that is at an angle, you suddenly start to see light coming in from there. Now in this new scenario, I2 is not equal to 0, and in fact, I2 will be much much larger than this blue I2 that I have drawn here. Now how do you explain this? So, there is nothing fancy here, you can actually think of this as a series of measurements, so clearly while it can look paradoxical when you say that by adding an extra filter you are suddenly seemed to be having increased the intensity throughput.

But what actually you are doing is that you would be able to say that by putting in this filter, you have generated some amount of intensity here, alright. Now that photons have a peculiar behavior, peculiar character which let them pass through this extra filter. Now how do you get that peculiar character? Classical, I mean there is simple ways of explaining it through wave theory of light, but you will see that the wave theory fails when you have to explain the fundamental nature of the light itself, either be photoelectric effect exhibited by PMTs day today in our life will be using that to detect light very regularly later on in the course.

So to be able to have a description that is consistent throughout where we do not have to switch at whims and wills of what the experiment it is. So it turns out that Dirac had a very relaxed formalism seem to provide a pretty nice continuum. Wit, that I hope that we will see you in the next lecture and we will talk more on the Dirac's bra and ket and their properties and how we can use to explain the polarization dependence. Thank you.