**Optical Spectroscopy and Microscopy**

**Prof. Balaji Jayaprakash**
**Centre for Neuroscience**
**Indian Institute of Science – Bangalore**

**Lecture – 6**
**Fundamentals of Optical Measurements and Instrumentation**

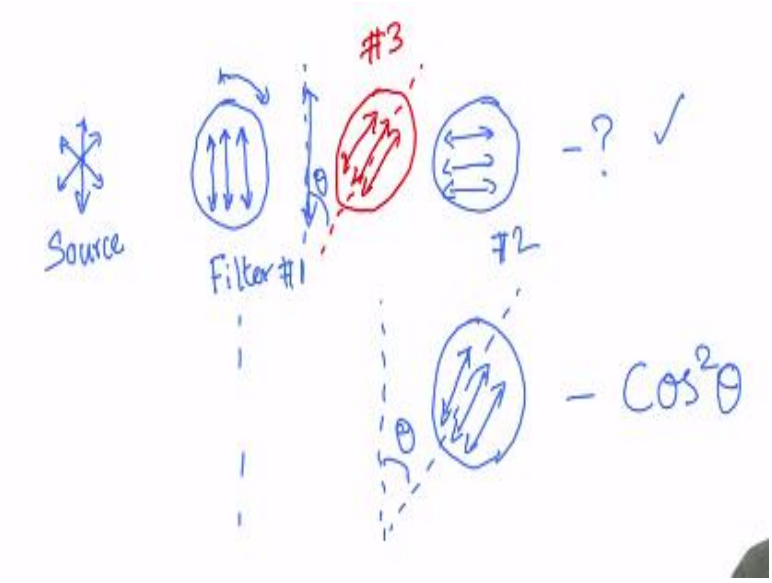
Hello and welcome to the lecture series on optical spectroscopy and microscopy. In the last few lectures, what I have been talking about is the impact of the absoluteness of the size principle that Dirac has formulated and hypothesized and what effect that has on simple measurements and as a consequence how the principles that we use almost every day in a laboratory that uses optical spectroscopy and microscopy such as localization of the photon in space.

I mean how fine a localization can we have in space and time can be directly derived from the fundamental principles that comes directly from this absoluteness of size, the uncertainty principle, we connected the momentum and the position uncertainty to obtain the localization accuracy possible for a photon and when you try to focus the light there by equating it to the diffraction limited spot size that one talks about in a microscopy related to the resolution and so forth so on.

As a followup we also looked at the uncertainty associated with the energy and the time and then related it to the notion of localizing the light in time, right, and I say that if you have to generate a light pulse that is of a very very very short time duration, what are the determining factors and what are the parameters that govern them, and towards the end, I was actually talking about a superposition principle or the introduction of the superposition principle and then I was describing you a simple experiment.

What it looks like a very simple and a trivial experiment involving optical crystals, the polarization crystals or polarizers, and the results that we get that can be perplexing the outset but I mean how I promised you that we can actually go about setting up some principles directly coming from Dirac’s formalism and then see how we can use it to explain the observations that we make from that experiment. Briefly the experiment is as follows.

**(Refer Slide Time: 03:35**




We are going to take a source of light. If we have a polarized source of light, then it is better, but if you do not have then what we can think of is a source of light which is having a polarization in all the directions, alright. So we saw that polarization is nothing but a property of the light such that when you actually pass this light through certain crystals, alright, so let us say this is the source of light and then when it passes through a certain type of optical crystals.

Actually I was indicating the crystals through this arrow, I mean these circles and the arrows inside an arrow, what it does is it generates a particular light of polarization by which I meant if I were to take another crystal okay. If it generates the light of particular polarization I said, the meaning of that is that if I take another copy of this crystal and then now what I am going to do is I am going to rotate because this is up to me how I actually orient this crystal with respect to the light, it is totally up to me.

I can define this in laboratory frame and then if I now rotate that crystal okay along this axis alright such that the arrows no longer point towards up and down direction but on the side wise direction and ask how much of the light that passes through, you will see that the amount of light that gets through this second filter right? This is our filter number 1 and this is our filter number 2 and we will see that the light that is coming out of this second filter is almost nothing, next to nothing.

That defines the light that is in between here right this light to be a polarized light, light with a polarization parallel to the first filter crystal axis and perpendicular to the second filter crystal axis. We also saw that it does not have to be 0 or 90 degrees, you could in principal put the filter, rotate the filter such that these arrows are at an angle theta okay, they are actually subtending an angle theta from, so you can actually extrapolate. So this is our original crystal axis right, this is parallel.

So what we have done is we actually shifted this and then if we rotate at an angle theta, then the intensity of the light that you see that is coming out from here would have a definite relationship with this angle and that goes as cos square theta. The intensity goes as cos square theta, alright. It will be lesser than what it would have been if it is parallel, but it is more than what it would have been if it is perpendicular. Now this per se is not a big surprising result except we are just describing the property of the crystal right and what happens to it when it is interacting with the light.

However, now what I said is the experiment gets little interesting when you actually introduce this third filter in between the first set, that is if I were to take another filter and then at this point if I were to place it alright. I am going to make some space, move this arrow little down and then make some space, so let us do that, so that is the initial polarization of the light right. Now if I actually introduce this filter third filter, I am using a different color just to indicate it is a third filter, but it is essentially the same crystal.

You are now taking a third copy, first copy, second copy, this is number 3, but now what you are doing is you have rotated it by an angle theta, not 90 degree, the theta right. So since this light is parallel we can actually measure this angle and that is theta. Now what you actually see is that suddenly the light starts to come out from here, now that is I mean at least from the outset looks little perplexing, what is so surprising here? The fact is that you are actually introducing a third filter which normally would have reduced the intensity.

But here what you are actually seeing is by introducing this third filter, you are actually increasing the intensity that is coming out of two filter system. Now classically, this can be very beautifully explained by describing the light that is emanating from the source as an electromagnetic wave and taking into account that the amplitude of the wave is oscillating with cos omega T and then there is an electric field which is a vector and then building up that and splitting up into components and so on and so forth, but the trouble is next step.

The step is in order for me to actually say if the light has come out from here or how much of the light it has come out, I need to be able to detect this light, right, I may be to be able to say hey the light is here or not here. Traditionally one of the ways in which we detect light is using phenomenal effect called as photoelectric effect okay and what is this? The photoelectric effect, I am going to go to the next page. So let us see.

**(Refer Slide Time: 11:31)**

So the photoelectric effect is basically the effect exhibited by certain metals which when you shine a light on them, they seem to eject electrons and of course the propensity with which this electrons can be coming out from those metals are different for different metals; however, very interesting property that photoelectric effect brings about is if you have to plot the kinetic energy of the electron that comes out of this metal as a function of the incident color of the light, not the intensity but just the incident color of the light

What you see is that it has this peculiar behavior that is there is no electron emission that is equal to 0 kinetic energy until certain point until certain color right, until a threshold color, but after which you start to see this. Now, this very characteristic behavior of the light, the threshold frequency beyond that defines beyond which there will be an electron emission is determined by what is called as work function of the metal.

It illustrates a very very important point that there seems to be a threshold behavior to this phenomena and the threshold behavior can be explained easily and only if you have to attribute photonic nature to the light, alright. So it is not dependent on, please note that it is not dependent on the intensity but does depend on the frequency, any color less than that it is not going to be able to eject out the electrons.

Again just bear with me for a minute, I am going to give you even more pressing to me in my mind, pressing illustration of the fact that it is really individual particles and not just an electric field, the wave of an electric field light is made of. So that comes from the understanding or by going to the fact of what we started out. We started out to say that I want to detect the light coming out from that experiment, and if I want to detect it, how do I detect it? So, I am going to make use of this photoelectric effect.

So that is a photoelectric effect. So the amount of electrons that get ejected out from such a process is minuscule and then detecting that and the current generated out of that will be hard to detect, so what people have done is that they have tried to develop devices which can actually amplify these small amounts of current that are generated through the photoelectric emission and this kind of detectors are something that we will be using in our instruments both in spectrometers as well as imaging microscope to generate images of various different kinds.

So, it is worthwhile to actually take a look at what would a typical photodetector look like? In here, I am specifically going to be sketching out a schematic of photomultiplier tube. The characteristics of this and all we would be seeing that in a detail later on in the course, but for now, let us look at the schematic of and look at the little bit of internal design of the photomultiplier tube, often abbreviated as PMT, alright. So now what we do is that we have these materials that are capable of ejecting out the electrons in response to the photon.

So pretty much using the photoelectric effect and so we are going to label this is as photocathode. Now, what is happening is that when the light strikes this photocathode, you have the process of electron emission, but these electrons are then accelerated right, so accelerated towards an internal structure okay. These electrons are then accelerated towards internal structure called a dynode okay.

Dynode is essentially we have the photocathode, the electrons coming out and photocathode is connected to the negative end of the battery and the ejected electrons come and heat internal structure called as a dynode. So since they come with some kinetic energy and they hit this dianode, these materials have the property of generating more such electrons. When more of these electrons are generated and again they are allowed to hit a cascading structure of the dynode and I will just in a minute talk to you about how we make sure that each of these electrons actually in turn hit these dynode.

So the way you do that is that you make sure that there is a graded electrical field that has been set up that is this is connected to a line in between. So the dynode number 1 is more positive than the photocathode itself; however, it is less positive compared to the dynode number 2 and so on and so forth. As a result, the one of the electrons that gets generated by the photoelectric event because of the photon interacting in the photocathode in turn generates a bunch of secondary electrons.

These secondary electrons in turn go, each one of them go and then hit subsequent dynodes generating a bunch of each one of, just to maintain clarity I am just tracing out one of the lines, actually you can see in principle this can actually be cascaded quite a bit ultimately before getting detected by an anode, okay. So now what people do or what one can do is that you can actually connect this to an ammeter, a current meter, and then you can actually measure the amount of current that is passing through this device.

Now, this would be proportional to like that a kind of not indicating the connections of the dynode, but they all come in between, so they all come progressively later on later, but the point here is that that is our final one of the traces of the electron that makes it to the anode. So now what you can actually do is that you can measure this current and then say how much of the photon or how much of the current that we are measuring than since the current is proportional to the electrons that are generated inside the photomultiplier tube, now these are in principle dependent on the photons that are falling on this.

In fact, they have a very peculiar gain characteristics they go, we will see that when we study about the signal generation mechanisms and the signal-to-noise ratios of the various detectors, but the point here is in proportion to the light intensity, we would be able to generate the signal, rest everything being constant. Now this can act as a measure of the amount of light that is falling on a detector that is passing through a system. Now here comes, the next to me a clinching and fantastic piece of an evidence for the nature of the light itself.

So you can actually in parallel to this ammeter connect an oscilloscope. Oscilloscope is a device that lets you see live the variation of the voltage or the potential as a function of time, often the signals that we measure in the lab are essentially variation of the voltage as a function of time is just that we could transpose any of the signals that you measure in terms of that. So this is a very very useful device and a very handy device to check and measure the signals that we generate in the lab. So what do we see in this oscilloscope?

So as I said you will be seeing a plot of voltage, the potential, in here the potential difference between the ground and the signal lead that you are measuring out here what you are talking about is the potential difference between these two ends, alright, so that is existing between in here these two ends across the oscilloscope as a function of time, and when you plot it, what you see is, so this is my time axis, when you plot the response at low enough intensity would look something like that, a peak in time right corresponding to the arrival of the photon.

I mean there are various different factors that determine the time difference. Let us call this as some tau d that relates this tau d to the photon arrival time at the front surface of the PMT. However, the important point here is that at low enough intensity, what I see is this negative current right because what we are actually detecting is the electrons, so what you see is a negative current and the negative potential corresponding to that that has a peak in a defined time.

As you keep increasing the intensity what you see is that you do not see an increase in the peak, I mean increase in the amplitude of this, rather you see many of such peaks coming in the same time window, and you keep increasing more and more, slowly the peaks get denser dense and denser before they start adding up and the as I show in the green curve what you see is that a simple DC curve when you have sufficient amount of photons that are bunched together.

You know in practice, you never get to the stage where it is the peak, I mean where the steady DC current is equal to there was a peak, at that point there is so much current, a lot of different things can get damaged, so but the fact is we do see that the individual peaks coming together reasonably close where in practice the peak would look somewhere around that point like half midway point that gives you enough number of photons to bunch together and then see that.

So that is a very clear evidence that what you measure as an intensity of the light that is made up of these individual events, these individual packets of energy that we call it as photons. So now together with this, the experiment that I described to you before become to explain this consistently becomes a problem. I mean the easier way out is to say that okay we have a dual nature, at sometimes it behaves like this and sometimes it behaves like that. However a more elegant way would be to have a continuous description that could actually fit in both these observations together.

It is that kind of a description that what that quantum mechanics offers you that actually where you do not have to switch between these 2 interpretations at all, and if I have to do that, then how do I do this? That is how do I attribute, how do I explain with a particulate nature that what happens in this experiment, alright? First and foremost when you say that the light that is coming out from the polarizer is polarized, what do I mean by that? I mean is the polarization collective property of all the photons or individual photons have that polarization.

The answer to that is the individual photons themselves have polarizations and in fact they always seem to be in line with the polarization axis of the crystal, I mean it depends on how you define it, but the way I have defined that is I am going to call the axis of polarization as the one which yields me a light whose polarization is parallel with. So this would be my axis of polarization okay.

So if I say that then what do we always see is that the light that comes out from a polarizer is of that polarization, so what is happening when you are actually talking about having a polarizer at an angle theta? So what is happening is that the fraction of the photons that are coming out, the interpretation would be the fraction of the photons that are coming out from this polarizer would be reduced, however if you go ahead and ask what is the polarization of each of these photons, they will always be aligned to this axis, alright.

Every individual photon seemed to be aligned to this axis. Now that poses a problem. Number one how do we even know that these individual photons are aligned to this axis if I do not put in another polarizer to explain? The answer to that lies in how we detect the light itself, so I will go back to my description of the photoelectric effect and the photomultiplier tube. Now you can ask a slightly different question here. The question here is I am going to vary the degree of polarization, how?

I am going to put a polarizer in front of the PMT and then start rotating it. When I start rotating it, I can actually measure the fraction of the electrons that are actually coming in and then I see that the intensity is going up and down. An another experiment that I can do is that I can actually ask the question about the directionality of the electron, right. The direction of the electron cannot be determined, you do not determine it by measuring the current, but actually you can think of putting in a photographic plate, people have done that.

So you can actually put in a photographic plate and then see the trajectory of these electrons, right they are electrons that are ejecting out, so you can try to see, there are ways to do that, you can put in a cloud chamber and so on and so forth or there are other ways of actually looking at the trajectories of the electron that does not matter but the point is if you look at the trajectories of the electron and there you can actually ask the question of angular distribution of these electrons or the electron trajectories with respect to the polarization of the light.

It turns out for a given polarization you always seem to have a maximum number or here what I am actually going to do is that the number of electrons emitted or ejected in that orientation, right. So if I plot that there is a preferred theta, right, this is the theta with respect to the angle with respect to the polarization direction itself, alright. So there is I mean we are measuring it let us say some theta here and what we see is that there is a preferred direction. So clearly, every individual photon resulting in this electron has a preferred direction.

It seems to be that there is a defined polarization for these individual photons. If there is nothing like that, what you would expect is that they will be randomly distributed that is in the entire region from 0 to pi, this one it mean 180 degrees you would expect it to be a simple straight line, but that is not the case that you see but you see rather a defined peak centered around particular theta indicating that each individual photons have a defined direction.

Now, let us put all these things together. We know that light is made up of photons from these individual peaks that we have seen and we know that each of these photons seem to be having a polarization associated with it, now through which we can go ahead and measure and ask what are the polarization of the photons that are coming out from the polarizer that is kept at theta or at any angle. Now what you see is that the photons that are coming out from the polarizer are always aligned to the axis of the crystal, okay.

Now then the way to explain this would be that somehow the act of we measuring what is the polarization of the photon itself seemed to have rotated the polarization of the photon okay. Now that is kind of an interpretation that we are going to lead into. Now this relates back to our initial statement or the Dirac’s initial statement that hey look there seems to be an absoluteness to the size and because of which when we are trying to probe a system and make a measurement.

The very process of making the measurement interacts with the system and changes or modulates the system and changes the state of the system and does not necessarily leave the system as such. So, this is exactly what is happening here. So now the very act of we measuring the polarization depending on what the initial state of the light it is seem to be changing its state if it were to be aligned with its crystal axis to start with, then nothing happens, it keeps going on, I can actually put another crystal here alright which is having the same orientation as that of the initial crystal.

The light will seem to go very smoothly, no problem at all. However the moment I rotate it by an angle some theta, it seems to be changing the orientation of the polarization of the photons. Now, this can be formally stated and then we can develop the formalism that is arising out from that and that we would see it in the next class. So in the next class, what we will do is we will take this as an example and state some of the axioms or some of the assumptions that we are going to put out right.

Then using that we will describe the system as an example of how we can actually use such a formalism to explain this behavior of light interacting, measurements in light right, and then using that as a basis we will look into how the light interacts with the matter. Thank you. I will see you in the next lecture.