Optical Spectroscopy and Microscopy
Prof. Balaji Jayaprakash
Centre for Neuroscience
Indian Institute of Science – Bangalore

Lecture – 5
Fundamentals of Optical Measurement and Instrumentation

Hello and welcome to the lecture on optical spectroscopy and microscopy. So far, what we have seen is that how the fundamental principles of quantum mechanics can serve us to help understand some of the basic notions that we have taken it for granted in this field and one of them that we have used uncertainty principle to understand how light cannot be focused to any arbitrary dimension and also how the light cannot be localized in time if you have to localize light and time, then what do we need for doing that.

Towards the end, I was trying to explain why we need another principle. Another principle of quantum mechanics is a superposition principle and what good it serves in understanding the properties of light.

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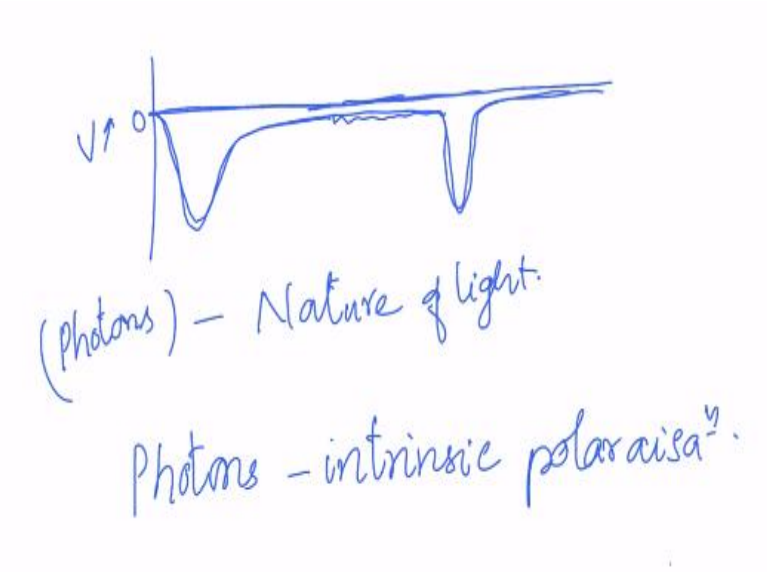

So, just now we looked at how the light detectors, photomultiplier tubes work, right. One of the properties of the output is that the electrons coming out from this photocathode seem to come out in a preferential direction, alright. So what do I mean is that they seem to suggest that every blip that we saw, the peaks that we see in response to the photon events right, these blips they correspond to the electrons that are coming out and what we see is that there is a preferential direction to this electrons suggesting that the individual photons by themselves have a polarization property. Photons seem to have an intrinsic polarization, right.

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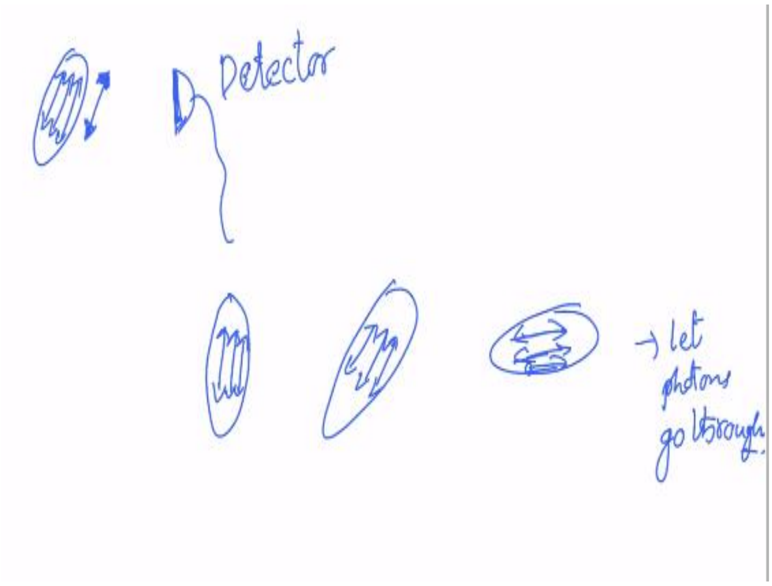

That is to say that if I were to keep a photomultiplier tube and then like let us say abbreviated as some kind of a detector here and then have a polarizer okay. What we see from this set up is that the photons that are getting detected through this detector seem to have a specific polarization direction, that is parallel to the axis of the last polarizer that we have used okay. Now, that is the key. We are still detecting individual photons, but those photons somehow seem to have the polarization of the last polarizer that we have seen.

Now, this together with the fact that if you were to introduce an extra polarizer that is at an angle theta to the initial polarizer that we started with, seem to let photons go through is really perplexing and it is not that easy to explain using classical mechanics, let the photons go through it is not that easy to explain. So now, then what do we do? So at this point, as I was telling this gives us some wonderful platform where we can actually see the usefulness of the superposition principle and the mathematical description that Dirac has proposed which we will be using right away after this experimental description.

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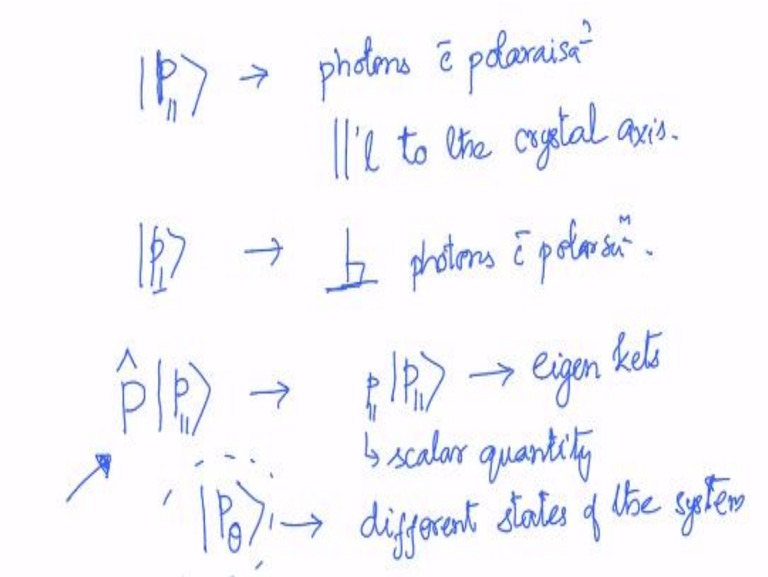

$|P_{\parallel}\rangle \rightarrow$ photons c̄ polaraisa^{n} ||'l to the crystal axis.

$|P_{\perp}\rangle \rightarrow \perp$ photons c̄ polarsa^{n}.

$\hat{P}|P_{\parallel}\rangle \rightarrow p_{\parallel}|P_{\parallel}\rangle \rightarrow$ eigen kets

↳ scalar quantity

$|P_{\theta}\rangle \rightarrow$ different states of the system

According to him, now the measurement that we want to make is polarization, so we could think of the photon, the photons polarization is represented in a vector, a state vector, and these state vectors have a particular property, that is so let us say I am going to represent this as P parallel. So this represents photons with polarization that is a polarization parallel to the crystal axis, clearly it would also mean we need to have another state that is represented by P perpendicular which represents the photons with polarization perpendicular to it.

Now what Dirac proposed is that the physical act of measurement corresponds to mathematical operation of using entities such as operator, right, the physical measurement corresponds to use of an operator, a process called an operator operating on these state vectors. So now when you write something like this, so we say that then this operator P corresponds to the polarization measurement. When this polarization operator operates on the state vector or the vector P parallel, its property it can be such that it leaves the system in its original unchanged state and with some kind of an output let us call P parallel by itself.

Now whenever you can write an equation like this, that is you have a state vector and operator operating on the state vector and when you do this operation, if you have the property of the state vector such that you were able to write like this where it is P parallel is just as some scalar quantity, it is just a number, then we called this as eigen kets. Dirac hypothesized that for physical measurements there are operators like this.

There is correspondence you would be able to find operator for any physical measurement on a system just the way for any system you would find a state vector, he said if you have a state vector and if you have a measurement process, you should be able to write an operator for that measurement process such that this operator when operating on a state vector will yield the state vector back, its analogous to you making a measurement and the measurement process itself leaving the system in the original state where it started with okay.

That is what we represent by this, right. You have a state vector P parallel and then when you operate on a P cap alright and you leave the system in P parallel state, and then it gives out some number okay. In this case, it could be just 1, but in general it gives out some number and then the original ket itself. Such kinds of kets are called eigen kets and then he said these corresponds to all the measurement value, all the observables value that you can actually get out from the system.

So in our case, there is a possibility of measuring P parallel and P perpendicular anywhere in between, which means in general we should be able to write ket something like this to represent different states of the system, which turns out is true you can actually write a state like that. However, there are special properties to an eigen ket as against some ket like this P theta.

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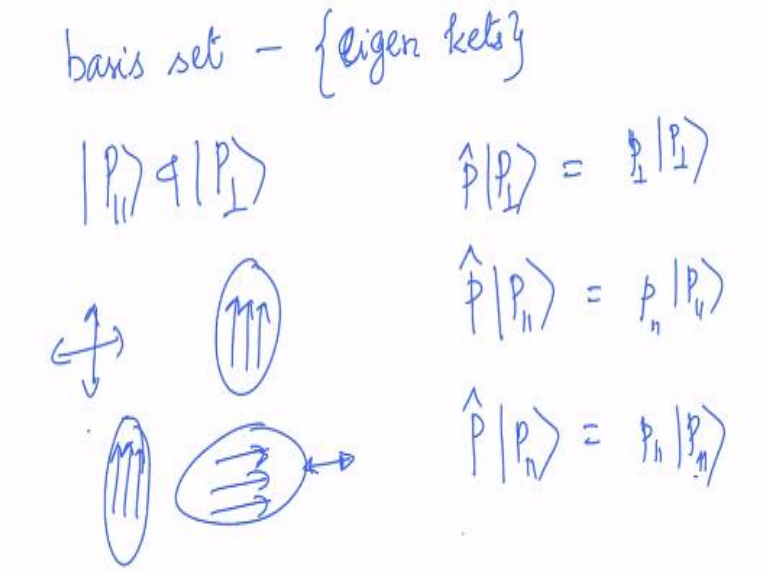

The property is that while this he said that the eigen kets of the operator P or any operator forms what he called as a basis set. The basis set is formed by all the eigen kets. So when we are talking about the polarization, it is always with respect to some kind of, I mean there is a reference with respect to a polarizer that we are talking about having in mind. So you could think of in here 2 possible polarization states as an eigen kets, which is P parallel and P perpendicular, right.

If you have them, then the process of you measuring the polarization or you probing the polarization when the polarizer angle, so we can actually take the right example again and then draw in a polarizer versus a polarizer that is orthogonal direction. It can be easily represented as P operating on a state which is like this and you are going to get back this and since P perpendicular is an eigen state, you should be able to write this in a similar way where I am just writing, maybe just to be consistent we will just say P some number okay.

So let us here then what is it, P perpendicular, will give you some number p perpendicular, this is a smaller p with the lip on top like this, but what is happening here is that if you take the polarizer that is at an orthogonal direction after this, what has happened is that you are doing this operation which is probing that and we have gotten a light that is parallely polarized, I mean that is corresponding to this state, but then you operate with this on and you are probing now with another polarizer at a 90 degree angle to the original.

So, then basically what you are trying to do is we are trying to probe how much, I mean basically what you are trying to see here is that what fraction of the light that is coming out from here is actually corresponding to P perpendicular alright. So as you can see here since we have generated a pure state which does not have any component of perpendicular light, you would get an answer corresponding to 0.

On the other hand in general, if we were to take an unpolarized light or a light that is polarized at an angle that is not necessarily aligned to the polarizers, the parallel polarizer itself, then we could represent that as P theta as I have written. Now, this can be thought of as superposition of 2 states. Remember this parallel and perpendicular are defined with respect to a polarizer, in our case I am always defining it with respect to the first polarizer and that is why previously when I had a second polarizer at an orthogonal direction.

Then what you are actually asking is that when I am making the second the P measurement, the polarization measurement, that measurement is of the second polarizer, the polarizer itself is at ninety 90 angle though when the polarizer acts on a light, what you see is that it is actually always telling you how much of the light is along its crystal axis, okay. So that is why you get it 0 because they are at 90 degree with each other, first and the second polarizer.

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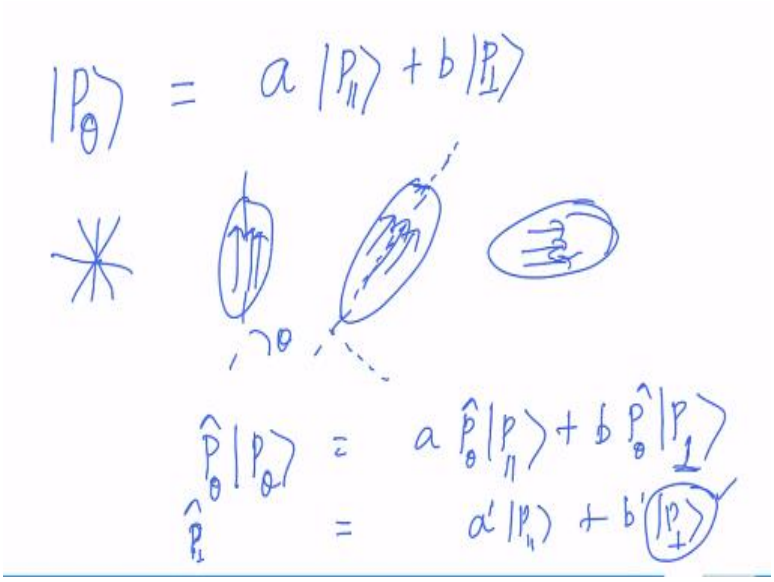

Now if you have it as at theta, then you can actually express this any angle theta as a linear combination of a P parallel + b P perpendicular or in other words now what we have been able to do is that we have been able to express something light state that acts sometimes as if it is parallel or sometimes as if it a perpendicular as a linear combination of these 2 fundamental states, thereby now if I go back and do this experiment right, where I placed my cross-polarizer here, sorry not cross, a polarizer at an angle theta, right.

What we are actually doing is that we are operating something like that equals a times P parallel and P perpendicular. Now, this results in a component, I mean, you will see that such an operation results in light which has both the parallel and the perpendicular components persisting, alright. So they do not, I mean since to start with they have the mix of parallel and perpendicular and you are operating with a polarizer at an angle. So now these states okay, these P parallel and P perpendicular, I am probing it with a polarizer that is at some angle theta, right, so that is the idea here, right.

So what you end up generating is that you leave these guys as a mixture itself, so some a prime P parallel + b prime P perpendicular. Now within this state if you have your next polarizer, this guy is perpendicular to the original one, comes and acts on it, it is going to pick up this component, and then you end up having light. Now that this idea, this notion of being able to represent the light as a linear combination of two states and then the act of measurement actually collapses them into either one of its eigen states.

For example in this case you can think of the act of our measurement is equivalent to asking the question of how much of the light is along the polarizer axis, either here or here or here, but if that keeps changing because we are changing the orientation of the polarizer, but the essential question we are asking is all the time how much of the light is along this axis versus a perpendicular axis, that how much is related to a and b coefficients.

I have not proved it, but I am trying to develop a motivation here of how these two can actually represent. This I mean writing in a linear combination can actually give you a way to explain what is seemingly a perplexing situation.

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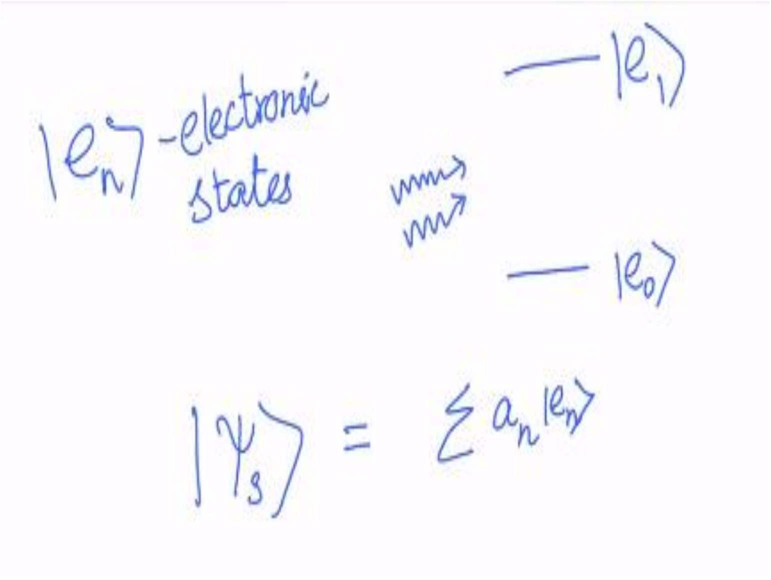

Now why are we actually talking about a superposition principle and how it may be relevant to what we are going to do in the light matter interaction? So, now let us see in a light matter interaction, what are we actually studying? So we know in matter and in optical spectroscopy, the relevant matter that we are actually investigating is mostly the electronic states okay, in general we represent it as let us say e0, electronic states let us represent it as en in general.

We are talking about in optical spectroscopy, we are dealing with the electronic states of the chromophore that we are interested in, alright, so e1 and so on and so forth. Later, we will see that there are some in between states that comes in handy for explaining some of the properties, but right now, what we are actually focusing on is these electronic levels and when electromagnetic radiation, light impinges on this, what happens to these electronic states? What happens to the occupancy of these electronic states?

Now in order to answer this, what we are going to do is that we know these electronic states are the stationary states of an atomic system or a molecular system or essentially a chromophore that we have in our hand. Now the bringing in the light alters this state of the system, that is our proposition, that we are going to say that it alters the state of the system; however, the alteration is very small, small enough that the resulting new states can be expressed as a linear combination of the previous electronic states, okay.

Electronic eigen kets or in other words, we are going to write new state of the system in presence of this light as a linear combination of previous known stationary states, stationary electronic states of the system, and then we would like to probe what is the energy associated with this system, right. Well, so we do that through specific operator called as a Hamiltonian operator and then how we proceed to set up an equation that describes this process and then how do we proceed to solve it? That we are going to see it in the next lecture.

As you can see I was building up all along to get you to this place where we can actually start writing this and then trying to understand how the light might interact with the matter, I will see you in the next class.