**Quantum Mechanics - I**

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**Lecture No - 41**
**The Jaynes-Cummings model**

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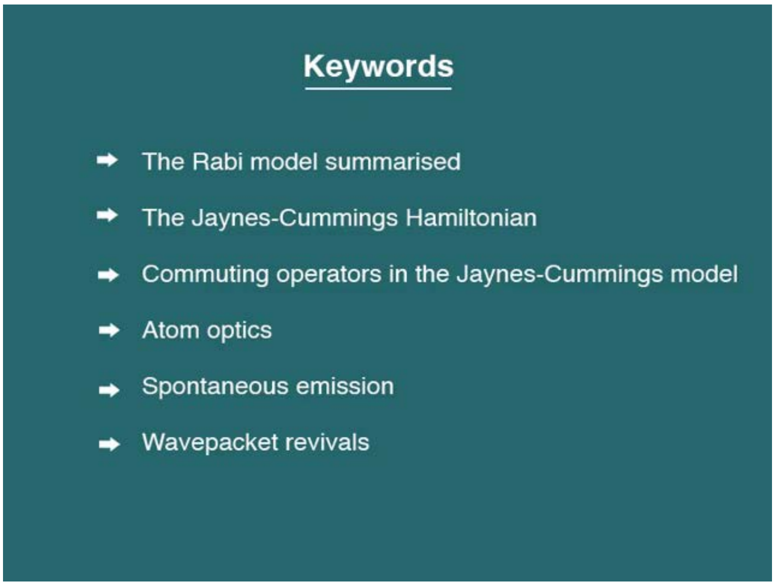


In the last lecture, we looked at the interactions of the radiation field with atoms. In particular, we looked at the Rabi model.

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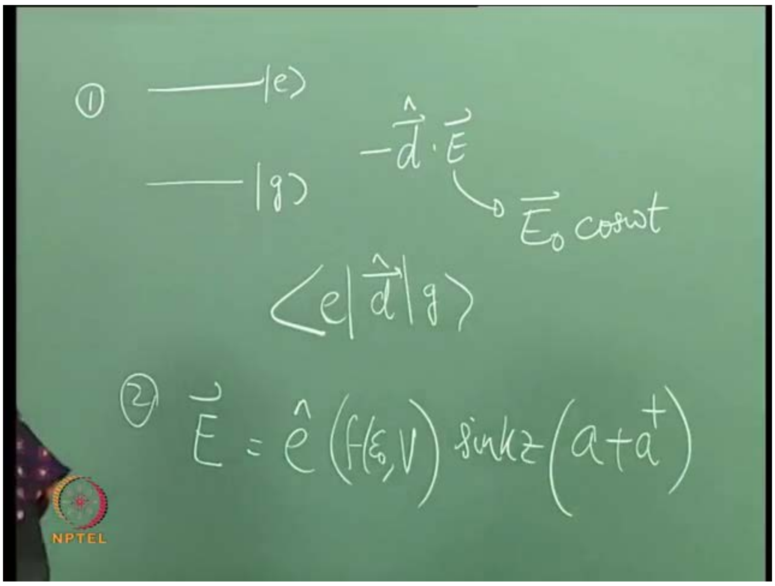

It is a semi classical model, in the sense that basically you have a two level atom. This is the ground state and that is the excited state and the interaction between this atom and the radiation field is through the dipole operator d. This is a single mode electromagnetic field in free space. This is the radiation field and we took this form for the field. So, that it was time dependent but varied sinusoidally. And then we saw that the population moved from the lower level to the upper level and back again, again in a sinusoidal fashion. There was a natural frequency in the problem the Rabi frequency.

And, there was a certain instant of time when even if the atom initially started in the ground state at that time, it would have moved completely to the excited state. And therefore, there was a population transfer to the excited state. Now, this is a semi classical model, in the sense that the atom operator, this is an operator and really we were interested in matrix elements of this form. This part of it was quantum and this electric field was nearly E naught Cos omega t. Then I moved on to another model and that was for radiation field inside a cavity, so fully quantum mechanical model.

So, the field is treated quantum mechanically in the sense that, the electric field is written in terms of the photon destruction and the photon creation operators. And essentially, in a situation like that, this was the 1st model. The 2nd one had a part from, this is the polarization vector, apart from constants that was a function of epsilon naught and the volume and sine k z. The electric field had a dependence on the photon creation and destruction operators in this manner as a plus a dagger, a is the destruction operator and a dagger is the creation operator. And then in that situation we could write down the Hamiltonian for the atom field interaction.

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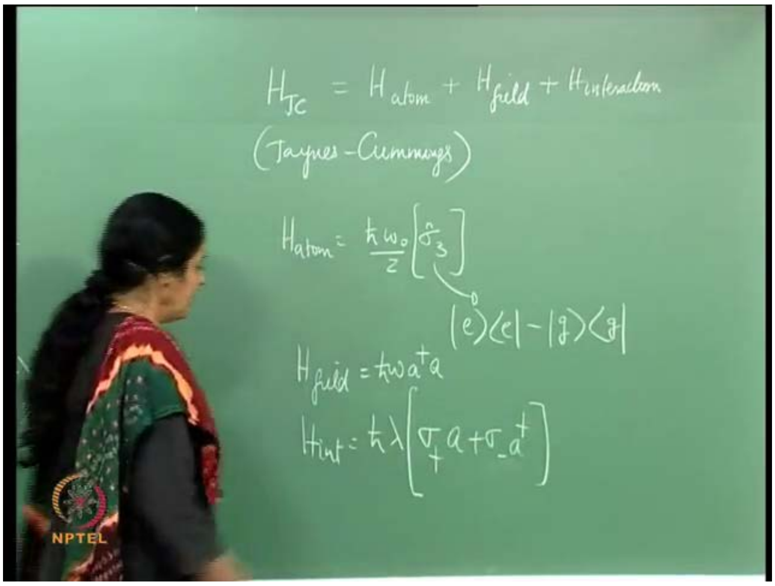


The Hamiltonian itself was the Jaynes-Cummings Hamiltonian. This had three parts. We had discussed this Hamiltonian and written out H atom as h cross omega naught by 2 sigma 3, with this operator is simply e e minus g g and h cross omega naught is this difference in energy.

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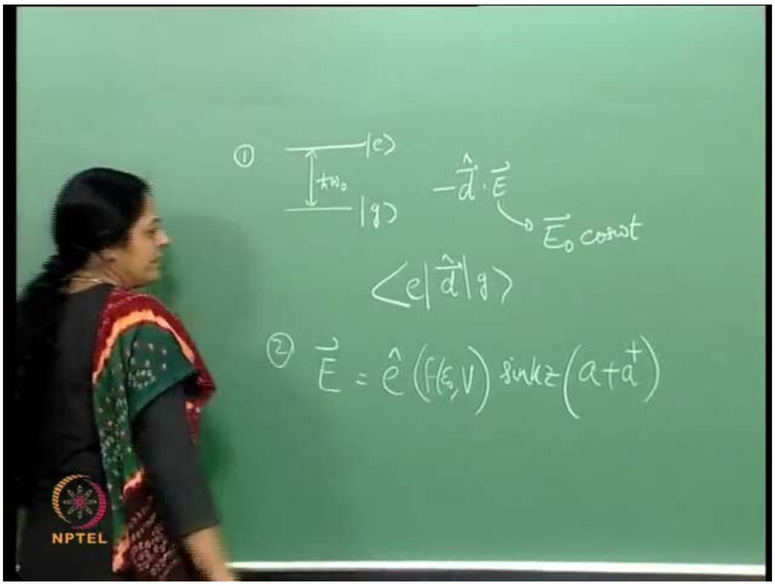


And then we had H field which was h cross omega a dagger a and then there was an interaction part which was h cross lambda sigma plus a plus sigma minus a dagger, sigma plus takes the state ket g to ket e, sigma minus lowers ket e to ket g. Of course, sigma plus acting on ket e is 0 and sigma minus acting on ket g is 0. And, you can see that this process would take the ground state of the atom to the excited state absorbing a photon and therefore, a photon got destroy. Whereas here, the excited state came to the ground state through sigma minus and in the process a photon was emitted by the atom. In other words a photon was created. So, this is the Hamiltonian. It has these three parts. I will now proceed for the better part of this lecture: discussing the Jaynes-Cummings model and the kind of dynamics that comes out of it.

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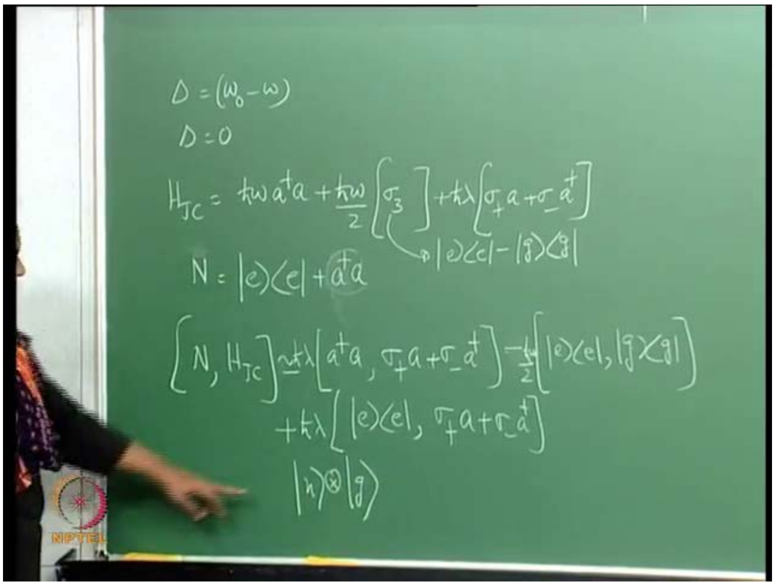


The detuning parameter of course, is omega naught minus omega. Now, let me work with delta equals 0. In other words, the frequency of the radiation field exactly matches the frequency omega naught here. Then the Jaynes-Cummings Hamiltonian clearly takes on this form: sigma 3 plus h cross lambda sigma plus a plus sigma minus a dagger. Before we look at the dynamics and what happens to the system when it evolves with this Hamiltonian, let us try to find out what are the various commuting operators in this problem. What are the operators that commute with the Hamiltonian?

Consider the operator N which I define as e e plus a dagger a. What is the commutator of N with the Hamiltonian? I will remove the hat, we will do well to remember that this is an operator. 1st of all there is a term: a dagger a here which suddenly commutes with itself, a dagger a commutes with sigma 3 because sigma 3 merely involves the atom operators and not the photon operators. So, essentially we need to find out, apart from constants, the commutator of a dagger a with this object. Now, this is as far as a dagger a is concerned. What is the contribution to this commutator from this operator?

Clearly, this commutes with a dagger a because this is an operator pertaining to the atom and that to the field. I need to worry about the commutator of e e with sigma 3 but e e commutes with itself and not with g g. So, basically it is the commutator of e e with g g. This comes with an h cross lambda, this comes with an h cross omega by 2. And, then of course, there is the commutator of e e with this object, sigma plus a sigma minus a dagger. Let us work with the typical state. For simplicity, we consider unentangled factored state n direct producted with g which means that the radiation field is an n photon state and g is the ground state of the atom.

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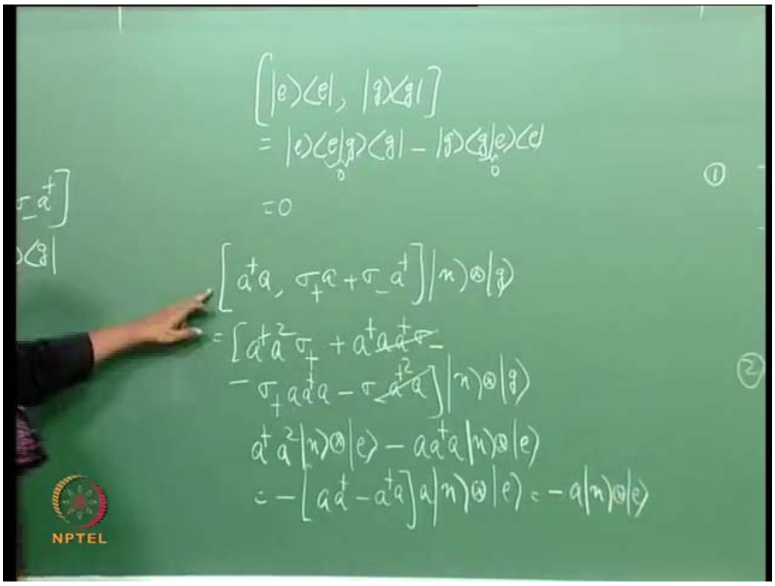


So, let me 1st look at this. This commutator is trivially 0 because it expands this way and g and e are ortho normal kets. And therefore, this is 0. So, I need not worry about this term. Essentially therefore, I simply have to look at the commutator of N with this last term, the interaction term. So, let us look at the commutator a dagger a with sigma plus a plus sigma minus a dagger, let us say acting on this ket. This is a direct product state of the atom and the field. Remember that sigma plus and a can commute with each other similarly, sigma minus and a dagger can commute with each other.

So, this acts on n g, sigma minus acting on g does not give a contribution. Therefore, I am left with this, sigma plus acts on g to give me ket e. So, I just have a dagger a squared ket n ket e, from this term, minus a a dagger a sigma plus acting on ket g gives me ket e. But, I also know that the commutator of a with a dagger is 1. And therefore, this is the same as minus a a dagger minus a dagger a a ket n, direct producted with ket e which is minus a ket and direct producted with ket e. So, this is this commutator which I have just now evaluated.

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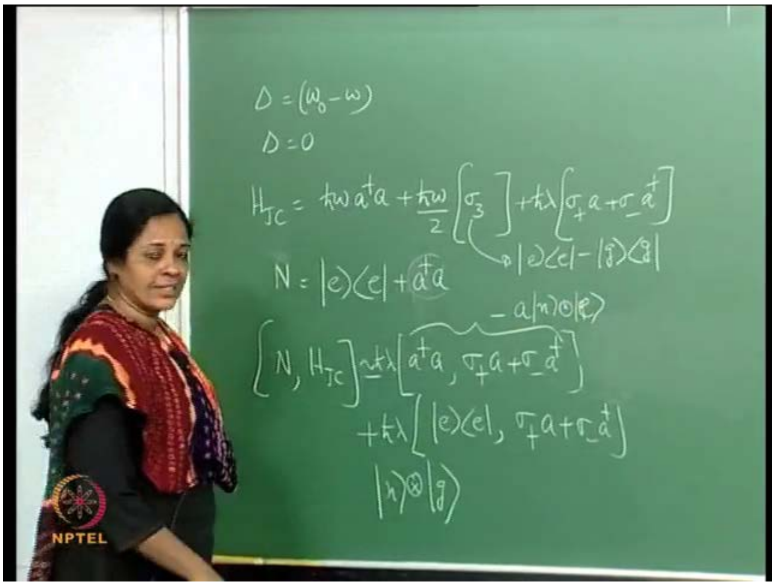


This commutator is minus a ket n direct producted ket e. And of course, a on ket n gives me a root n ket n minus 1. But, for the momentum I am just keeping it as such. I need to evaluate this commutator. What does that give me?

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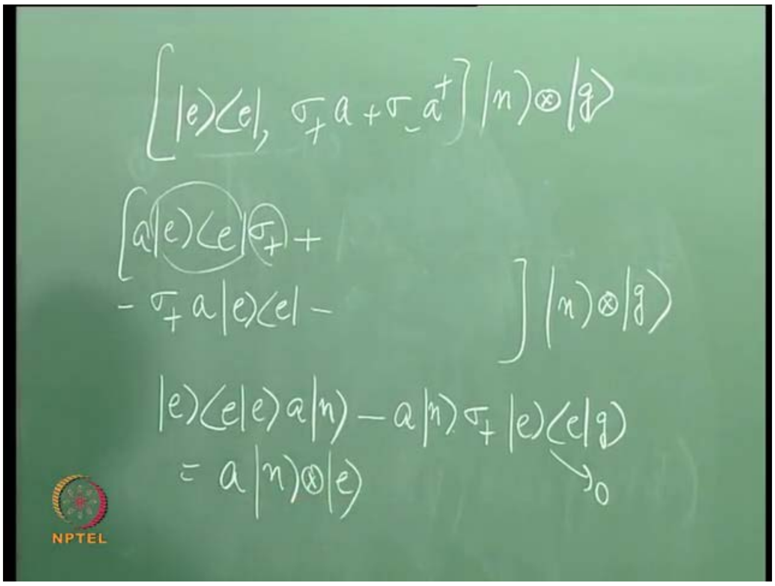


Once more, I need to find out the action of this commutator on that state. This plus, I am expanding out the commutator acting on the state, the factored product state ket n ket g. Once more, sigma minus cannot contribute, sigma plus takes ket g to ket e. So, I have the 1st term is this: a acting on n minus the 2nd term, is again a acting on n sigma plus e g, but that is 0. Note that the ordering is important. This object does not commute with this. Since, that is 0 and there is a contribution here, this is a ket n direct producted with ket e. So I have evaluated this.

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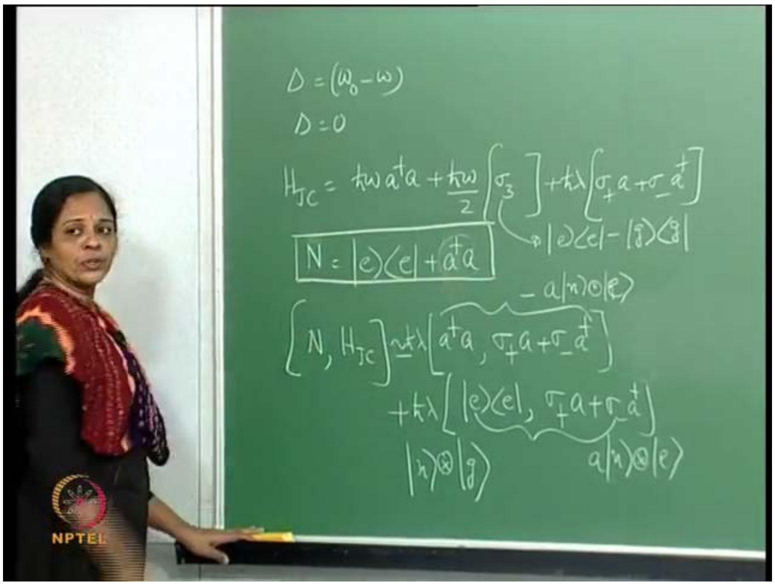

And, as you can see the 2 cancel out and therefore, I have shown that this operator N commutes with the Jaynes-Cummings Hamiltonian. I could have used any other combination of states: direct product states, any basis state in general and I could have shown that this commutator is indeed 0.

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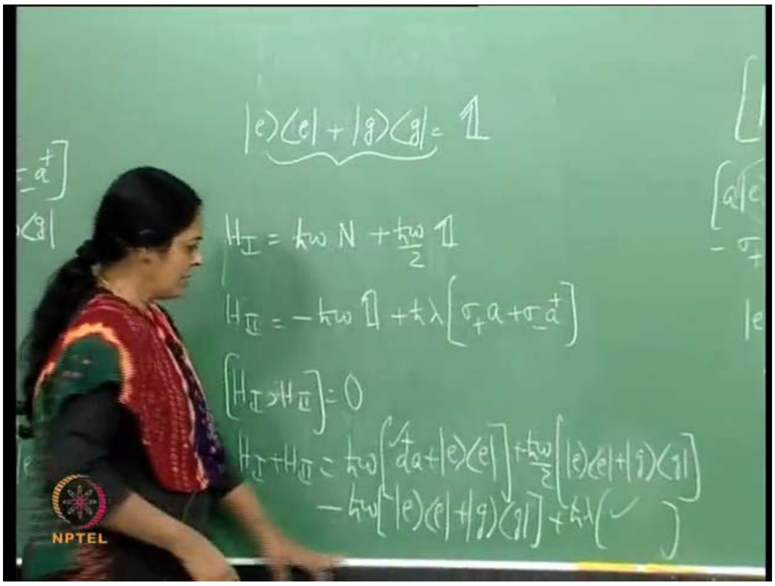


Of course, there is an expansion for the identity operator in this manner. Because, recall that there are only two states, it is a two level atom effectively. This is not perturbation theory. The population transfer is primarily between two levels and therefore, I have this identity. I now define a Hamiltonian h cross omega n plus h cross omega by 2 identity and another Hamiltonian which is minus h cross omega identity plus h cross lambda sigma plus a plus sigma minus a dagger, the familiar interaction term of the Jaynes-Cummings Hamiltonian.

If you now look at: H 1 and H 2, they commute with each other. N commutes with the identity. We have just now shown that N commutes with this part, the interaction part of the Jaynes-Cummings Hamiltonian. It is clear that the identity operator commutes with everything. Further, what is H 1 plus H 2? When I expand N in terms of the field operators and the atom operators and the identity operator in terms of the atom operators, I simply get the following. This simply becomes the original Jaynes-Cummings Hamiltonian. (Refer Slide Time: 14:04) Here is your h cross omega a dagger a. I need to have and this part is already there.

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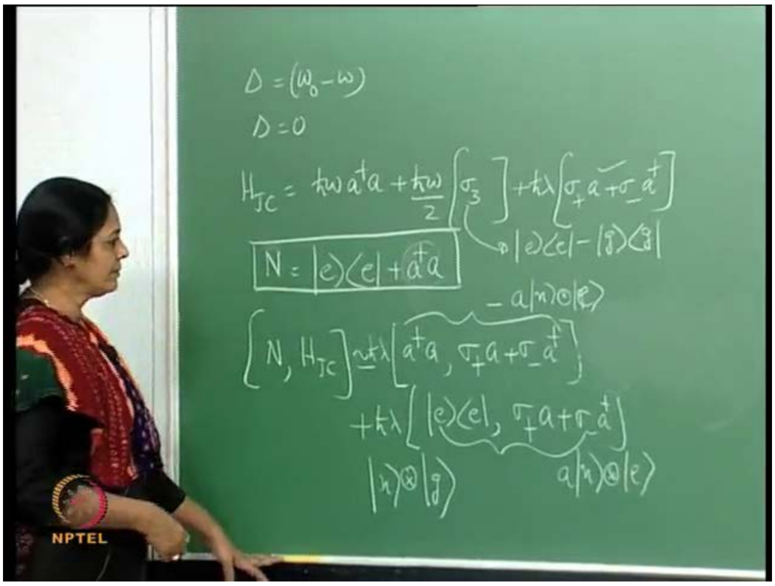


And now, between these it is clear that I have h cross omega by 2 ket e bra e, that is one operator and I have a minus h cross omega by 2 ket g bra g. Thus, giving me sigma 3.

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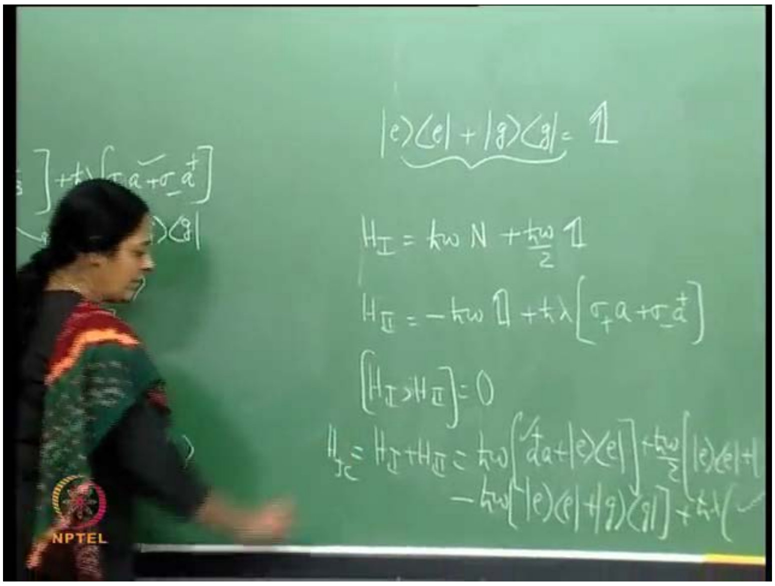


So, indeed I can write this Hamiltonian the Jaynes-Cummings Hamiltonian as H 1 plus H 2 .

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Where I have set the detuning parameter to be 0, and now, I work with this Hamiltonian and try to see what kind of dynamics comes out of this.

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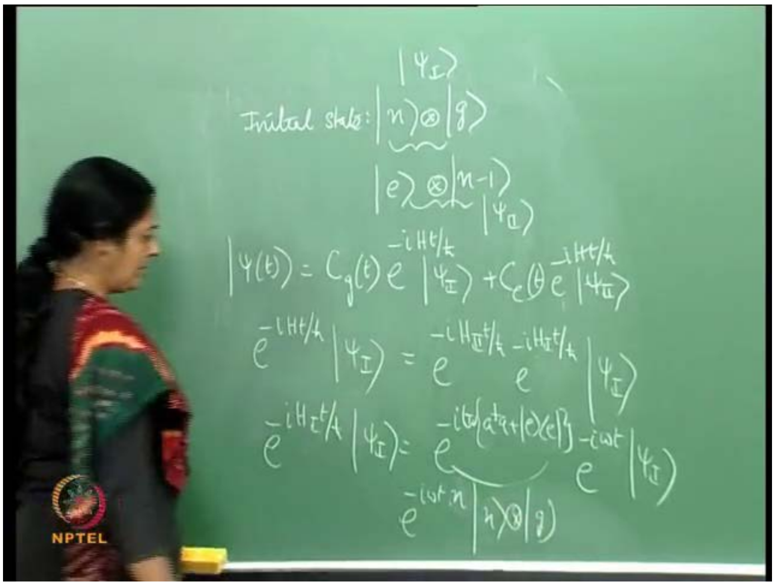


Let me start with the state: the factored state, factored product state of the descent angle state, n direct product g. That means, it is an n photon state. Initially, this is my initial state and the atom is in the ground state. What are the various states that are possible here? Of course, the ground sate could become the excited state or this could have happened only if a photon was absorbed. And therefore, n went to n minus 1. So, what is an arbitrary state of this system which means at any time t what is the state? Perhaps, I can write this as C g of t e to the minus i H t by h cross.

Let me call this psi 1 and this as psi 2. These are basis states. I use e because psi 2 has the atom in the excited state and I use g here because psi 1 has the atom in the ground state. Recall that these are not functions of time. They are basis states. This is the manner in which the basis states evolve and in general I have some superposition coefficients. But, let us now look at e to the minus i H t by h cross say on psi 1. This has two parts which commute with each other: e to the minus i H 2 t by h cross, e to the minus i H 1 t by h cross. They commute with each other acting on the state psi 1. But, what would this give me?

If I look at the e to the minus i H 1 t by h cross psi 1, this has 2 parts. H 1 itself is here. It has an N and it has an identity. So, N has a dagger a plus e e and then it has the identity operator. Of course, this comes with the coefficient which I have not put down. It is omega there and then e to the minus i omega t psi 1. Now, this is simply a phase. Now, if you look here, this commutes with this. I can always write this as e to the minus i omega t a dagger a e to the minus i omega t e e, acting on psi 1. If you look at psi 1 that has a g in it and if I expand it its only the leading term that will contribute because e and g are orthogonal states.

So, there is no contribution from here and as to this it is simply picks up an n leaving the original state as such. What we have therefore seen is that the effect of H 1 is not to produce any interesting dynamics but to merely give an overall phase. So, let us not worry about the action of H 1 of t.

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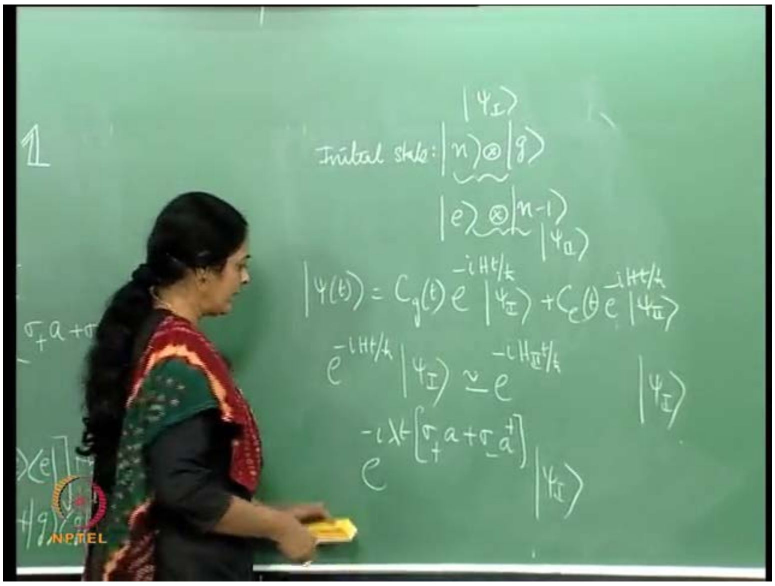


This would therefore, as far as the dynamics is concerned, this would simply amount to looking at the effect of H 2 of t on psi 1. Again H 2 of t, H 2 times t not H 2 of t, H 2 times t has two parts. One is the identity which is not going to change anything. It is merely going to produce an overall phase. So, the only nontrivial contribution comes from e to the minus i lambda t sigma plus a plus sigma minus a dagger psi 1.

I will use the same argument to show that here also I need to only worry about what the interaction Hamiltonian does to psi 2. Everything else becomes an overall phase. What would happen here? 1st of all psi 1 has g and therefore, sigma plus acts on g to make it e. I expand this exponential. The leading term is simply n direct producted with g and then of course, there are effects because of the other terms in the exp1ntial. Whatever it is, the only two states that can contribute are ket n direct producted ket g and ket e direct product ket n minus 1. And therefore, all this simply amounts to some combination here which is a function of time.

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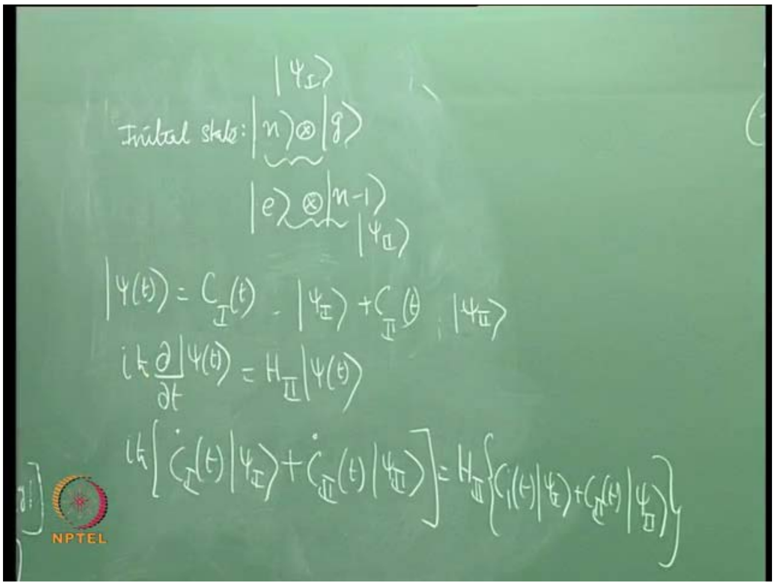


I will call that C 1 of t ket psi 1 plus C 2 of t ket psi 2. So, apart from overall phase which we need not worry about as far as a dynamic is concerned, we need to only consider the interaction part of the Jaynes-Cummings Hamiltonian. And there to finally, what I have can only be a superposition of these two states. This is something I could have told even earlier because if only two basis states are allowed effectively in our problem at any instant of time, psi of t must be a combination on those two basis states.

So, even as we did in the semi classical example let us look at the Schrodinger equation. So, here again I need to worry only about H 2 psi of t as far as the dynamics is concerned. And, this gives me i h cross C 1 dot of t psi 1 plus C 2 dot of t psi 2 that is a left hand side of the equation, equals H 2 C 1 of t psi 1 plus C 2 of t psi 2. This is the Schrodinger equation. So, let us see how this simplifies.

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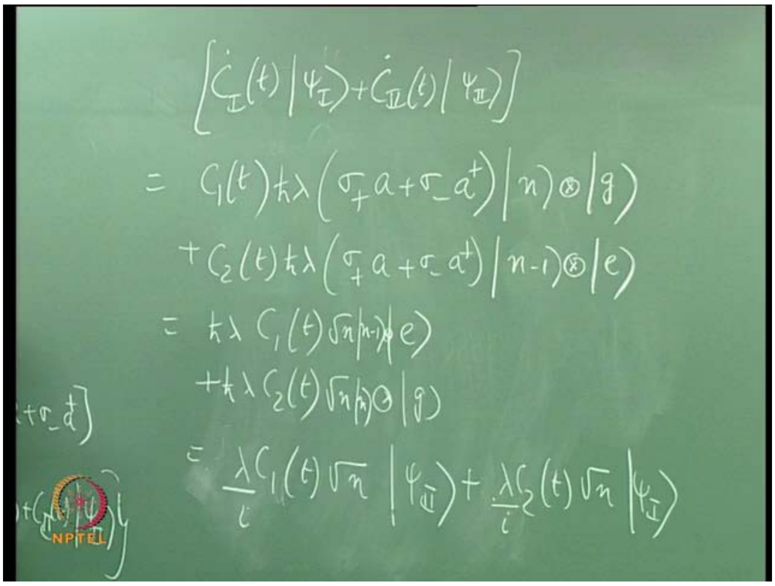

The right hand side, let me write that again. The left hand side is C 1 dot of t psi 1 plus C 2 dot of t psi 2 apart from an i h cross.

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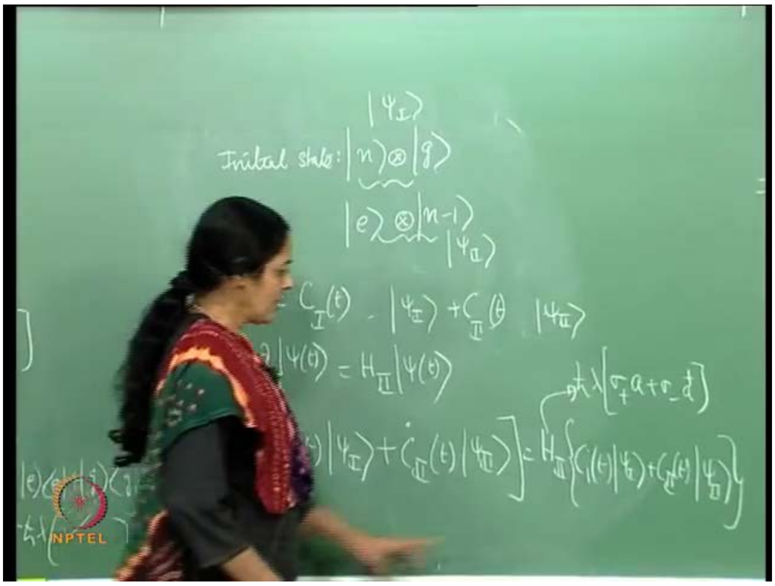

H 2 essentially has h cross lambda sigma plus a plus sigma minus a dagger. So, if you look at this, what would I have? I will have C 1 of t h cross lambda sigma plus a plus sigma minus a dagger acting on psi 1, plus C 2 of t h cross lambda sigma plus a plus sigma minus a dagger acting on psi 2. Notice that, psi 1 is n cross g and psi 2 is n minus 1 direct producted with e, by cross I meant a direct product. So, this is just h cross lambda C 1 of t sigma plus g gives me e and a on n gives me root n ket n minus 1. This of course, does not act and give you anything substantial, plus h cross lambda C 2 of t sigma minus gives me g and I have an a dagger which gives me root n ket n.

So, essentially I have h cross lambda C 1 of t root n psi 2 plus h cross lambda C 2 of t root n psi 1. Of course, I can cancel the h cross on both sides of the equation. Put the i here on the right hand side and this is what I have. So, here we have the equations.

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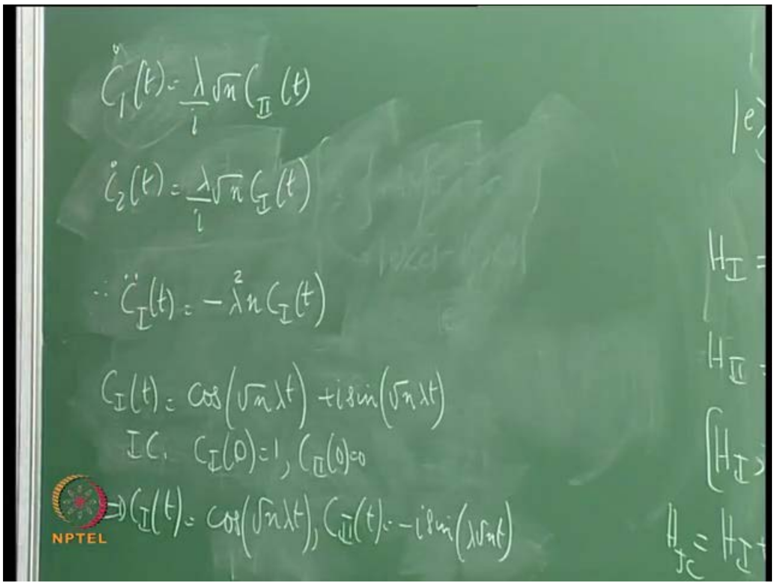


C 1 dot of t is lambda by i root n C 2 of t and C 2 dot of t is lambda by i root n C 1 of t. Of course, these are coupled equations. We can differentiate them once more and decouple the equations that gives me trivially C 1 double dot of t is minus lambda squared n C 1 of t. What is the solution?

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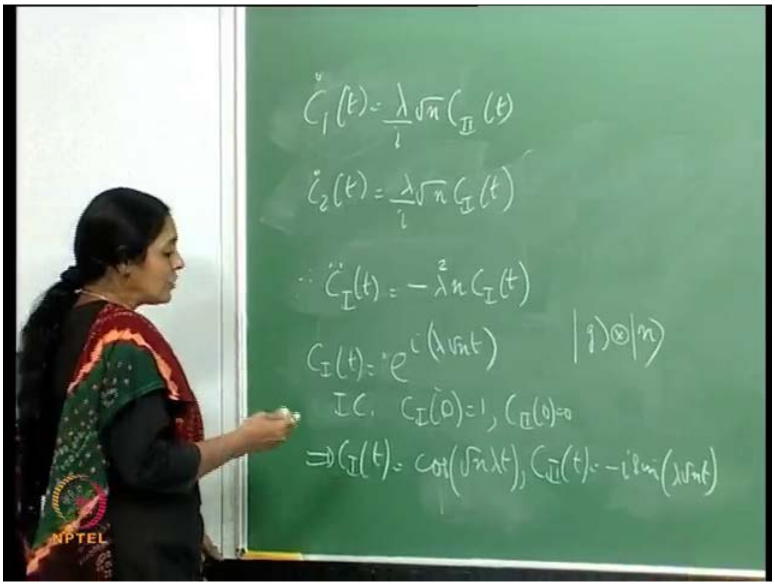

Now, the general solution would be a Cos root n lambda t plus, well I can write the general solution as e to the i lambda root n t. But, you see the initial condition will now play a role. Let us choose the initial condition that initially the population was all in the ground state that means the initial state was g direct producted n. And therefore, C 1 of 0 is 1 and C 2 of 0 is 0. That clearly tells me that C 1 of t will only have the component coming from the cosine. It is Cos root n lambda t and C 2 of t is minus i sine root n lambda t. This is very much like the model that we studied yesterday, the Rabi model. Of course, there is a frequency here which is given in terms of root n lambda. But then otherwise there is merely a population transfer from one state to another state. And, we can see that the probability of being in the initial state is Cos square root n lambda t and the probability of going to other state is sine squared root n lambda t. No difference from the semi classical counterpart.

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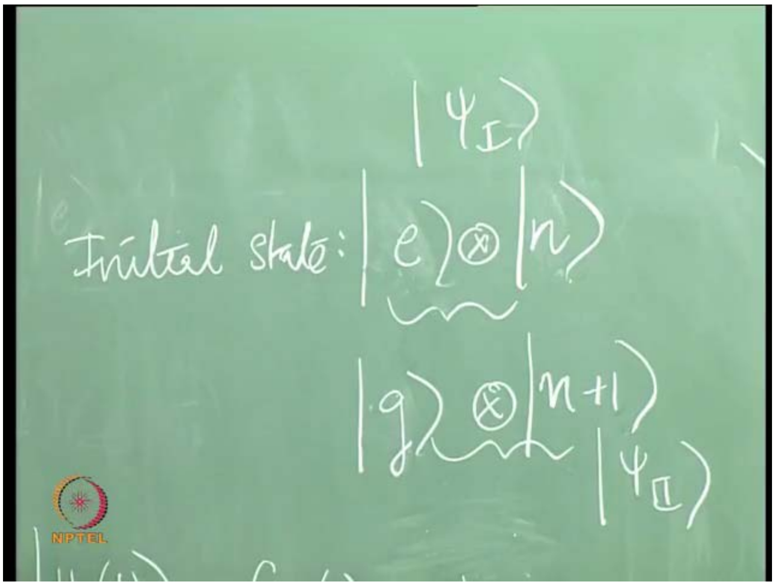


But, on the other hand if I had started with an initial state which was in the excited state say e n and then the atom could have come to the ground state. So, e would have become g and n would have become n plus 1. Now, if I repeat the calculation everything will go through and it is a simple matter for you to check out that root n would be replaced by root of n plus 1. You would have the following.

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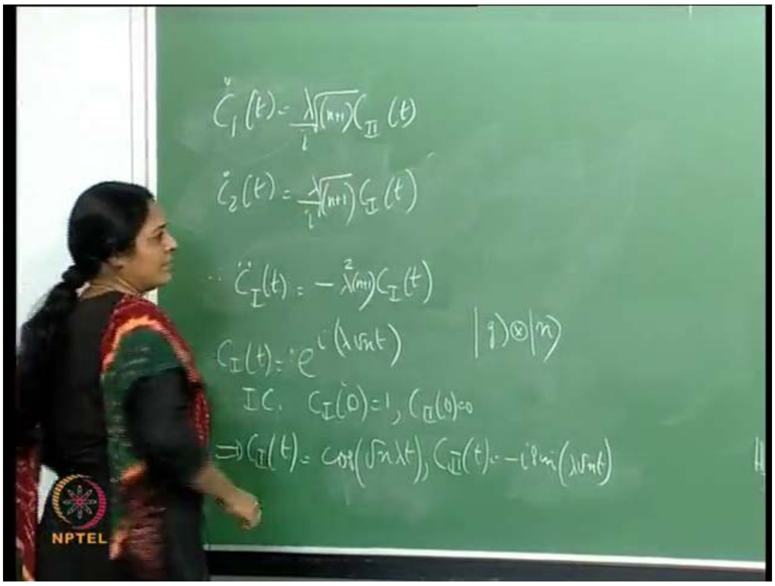

So, you would have a situation where root n is replaced by root of n plus 1 and that would have come about because when sigma plus acts on g its counterpart is a and a acting on ket n plus 1 is root n plus 1 ket n. Similarly, when sigma minus acts on e its counterpart is a dagger acting on ket n and a dagger on ket n is root n plus 1 ket n plus 1.

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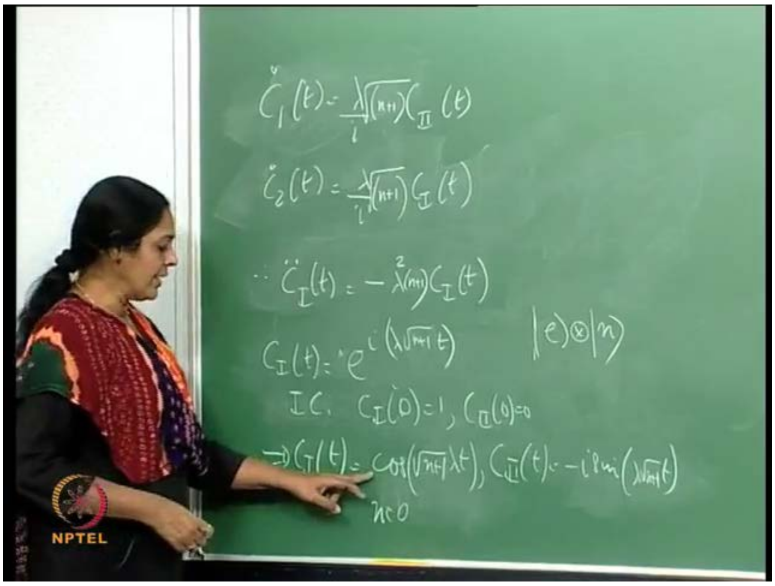


What does that mean for this solution? It means that if I had started with an initial state ket e ket n direct product, this is my initial state in this case, ket e ket n. Everything will go through except that here I will have n replaced by n plus 1. Now, in the Rabi model its clear that since the radiation field was e naught Cos omega t, if you switched of the field there would be no transition from the excited state to the ground state. But now, look at what you see here. If there were no photons in the radiation field suppose n were 0 even then you have C 1 of t is Cos lambda t and C 2 of t is minus i sign lambda t.

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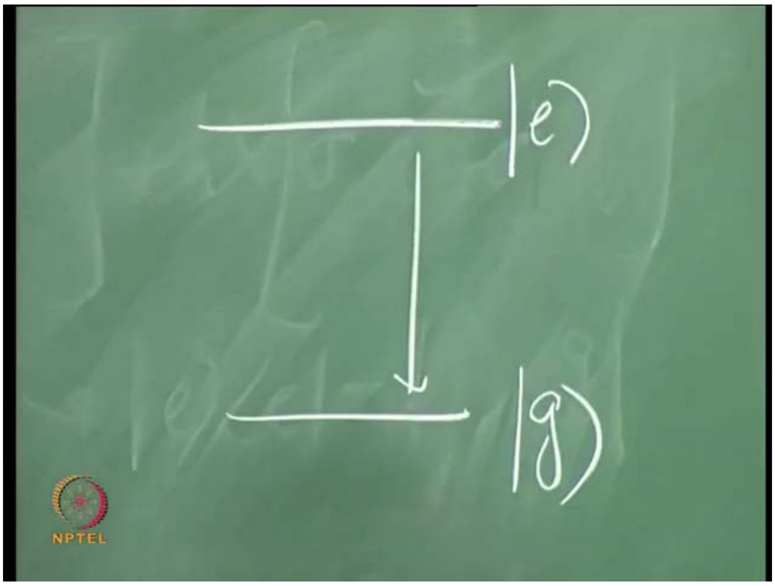


In other words, there is a non zero probability of transfer of population from the initials state ket e of the atom to the final state ket g. In the absence of the external field, in the absence of the radiation field this is precisely what I remarked about in an earlier contest when I discussed spontaneous emission. Spontaneous emission corresponds to a situation where there is no photon which is interacting but the atom in the excited state could randomly give out photons and come down to the ground state. This is a purely quantum mechanical phenomenon with low classical counterpart. And, that is what we see here also, quite unlike what we saw in the semi classical model.

So, the atom: emits photons absorbs photons, emits photons absorb photons. This keeps happening spontaneously quite independent of whether there is an external radiation field interacting with the atom or not. So, the principle of spontaneous emission that concept which I explained in one of my earlier lectures your merely seeing it is signature out here in this case. So, this is another place where you see it and that is the essential difference between a fully quantum mechanical model like the Jaynes-Cummings model and a semi classical model like the Rabi model.

Now, instead of looking at a situation like this where the radiation field is in a photon number state and therefore, there is merely a sinusoidal variation of the population transfer and the only interesting phenomenon that we can see is spontaneous emission essentially.

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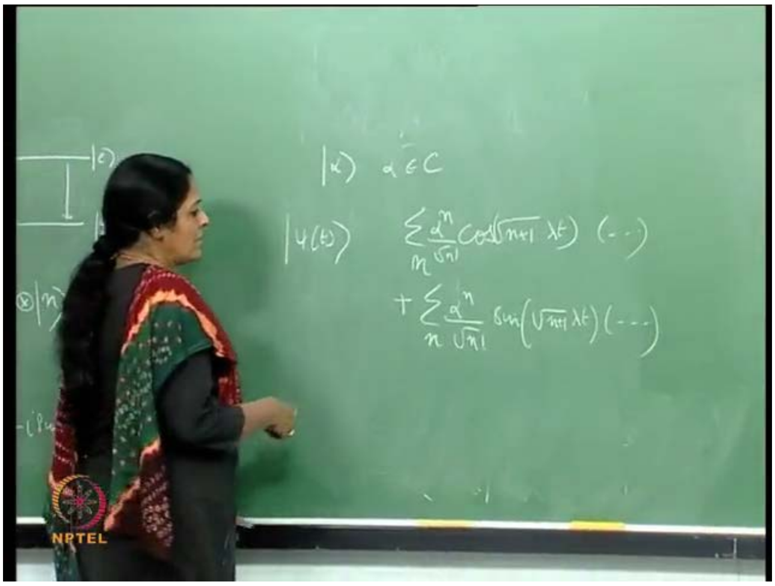


You look at a situation where the initial state of the radiation field is the coherent state for instance, some interesting superposition. Now, in that case the matter is going to be very different because an arbitrary states psi of t is going to involve a summation over n Cos root of n plus 1 lambda t apart from alpha to the n by root n factorial and a whole lot of terms. Similarly, it would involve sine root of n plus 1 lambda t apart from a whole lot of factors. 1st of all of course, psi of t is an entangled state you might start with the factored product state but the dynamics entangles the state and it rarely happens that the state comes back to its original factored product state. That is call a revival and I will comment about it shortly. In general it is an entangled state as time evolves although initially it was an unentangled state. Further, the dynamics is very interesting. As I said, if you look at relevant quantities they could come back to their original values at certain instants of time or over a certain period of time.

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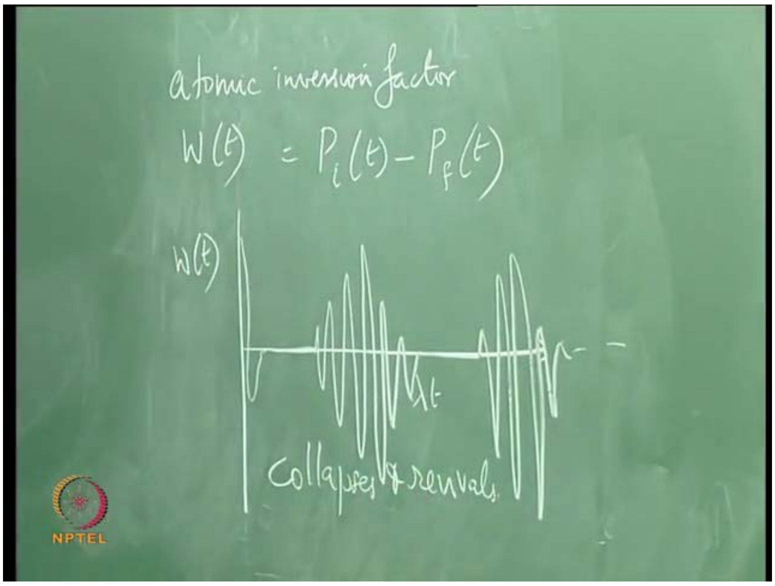


In this example, if you look at the population atomic inversion factor as a function of time which is the probability of being in the initial state at that time minus the probability of being in the final state at that time. This shows a very interesting aspect which is a non classical effect called collapses and revivals. What are collapses and revivals? Over a certain period of time there is quiescence or the inversion factor states put at a given value and then there are: revivals that means rapid oscillations again a quiescent state and then there are revivals rapid oscillations and so on.

So, the system collapse to a quiescent state revives, collapses revives so on and so forth. These collapses and revivals are seen in the Jaynes-Cummings model with no classical counterpart. In general, a revival could happen under very many conditions essentially the return of a system to itself would indicate a revival. It could even be the state of the system. For instance, the wave function for a system could come back to itself apart from an overall phase at certain specific instance of time periodically coming back to itself.

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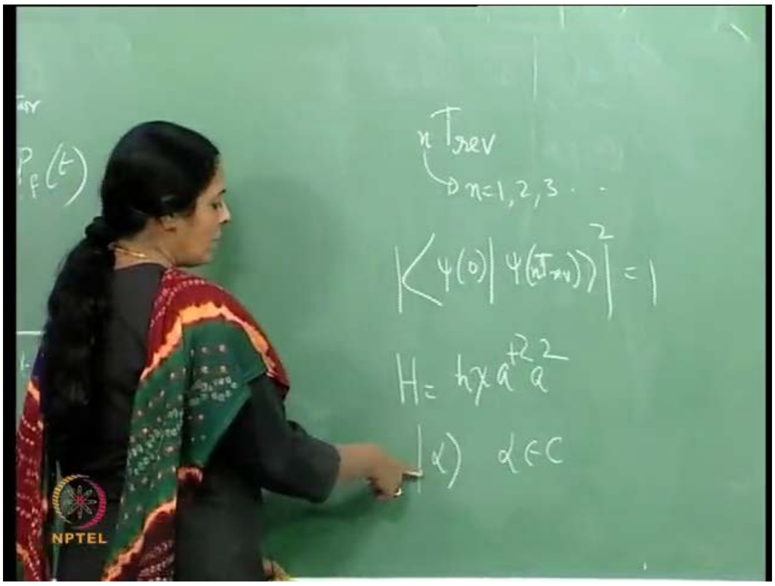


So, that it comes back apart from an overall phase to its original value at instance separated by a basic revival time called T revival. In general, this does not happen. This happens because of the dynamics because of certain non-linear interactions because coefficients, relevant coefficients, a tailored just so and so on. Without looking at the details I merely want to point out to you, the kind of rich dynamical structure that quantum physics can show. In units of the basic time of revival T rev you can sometime see that the system comes back to itself, apart from an arbitrary phase.

And therefore, this is 1 certainly therefore, all expectation values come back to themselves and you would say that the system has revived. I want to show collapses and revivals for a different model. The model is the ket Hamiltonian, I spoken about earlier. So, this is an effective Hamiltonian and the initial state that I consider is ket alpha which is just the coherent state of light. So, initially it is a Gaussian in position space. As it evolves through this Hamiltonian the Gaussian no longer preserves its property and in fact changes very wildly but it turns out for details which I will not go into right now.

Through some very interesting periodic properties at n times T rev there are revivals. The wave function comes back to itself at these times apart from an overall phase. And therefore, all expectation values come back to themselves. In this situation, we can calculate certain expectation values and see how exactly they behave. So, let us look at these expectation values. As you know the quadrature variable X is a plus a dagger by root 2.

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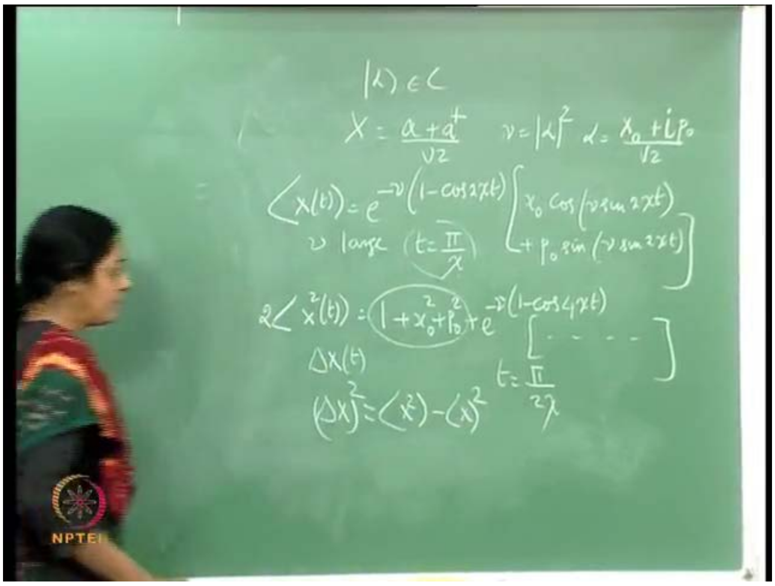

I have defined mu as mod alpha squared, ket alpha was the coherent state. And, alpha itself has a real and an imaginary part which I referred to as X naught and P naught, X naught by root 2 and P naught by root 2. Now, if you compute X as a function of time, the expectation value of X as a function of time remember that the initial state was a Gaussian. But, as I indicated the Gaussian losses its shape and form almost instantaneously as it moves through the Kerr medium. And, the manner in which the observable various in time is given by this expression.

If you look at this expression suppose nu were chosen large, the exp1ntial term will dominate. It comes with the negative sign out here and therefore, X of t really does not change with time because there is an e to the minus large quantity here except those instance of time where t is pi by chi or n pi by chi. So, let us look at just pi by chi so t is pi by chi and then you see this quantity becomes 0. And therefore, all these objects start contributing and therefore, at the time t equals pi by chi you find that X of t would show a change in its value once more going back into a constant value and almost constant value for other times.

So, only at this instant you would find that there is a large variation in X of t. Now, if you computed X squared of t equivalently delta X, you could have computed P squared of t equivalently delta P of t and so on. The expression would be like this: apart from some overall constants which add up you have an e to the minus nu 1 minus Cos 4 chi t times objects like this. As you can see for nu large X squared of t would essentially be this apart from a factor of 2. And therefore will not show any change in time but then when t is pi by 2 chi you find that once more this quantity disappears. And therefore, there is contribution from here and there is a sudden jump in a plot of X squared of t, expectation X squared of t versus t.

Similarly, expectation P square of t versus t or even delta X versus delta P because delta X the whole squared as you will recall is expectation X squared minus expectation X the whole squared. And, that is what I will show in animation now.

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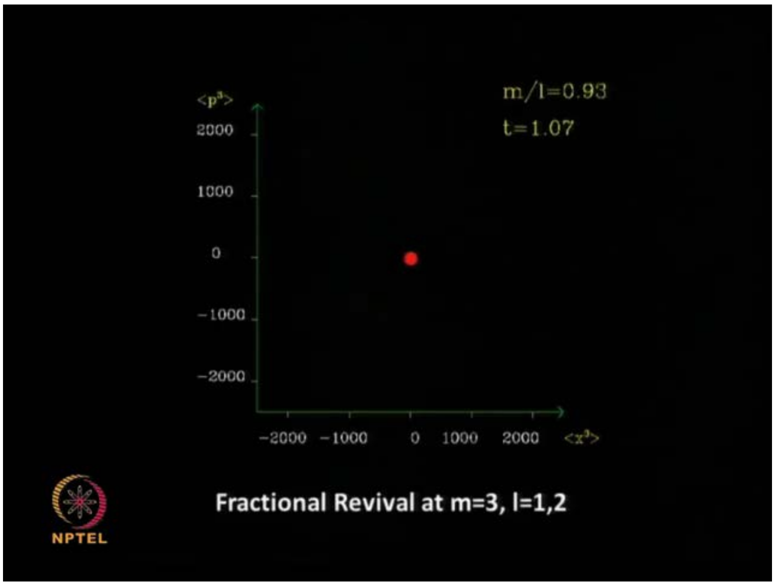


So, the 1st plot is to see how exactly things vary at instance pi by 2 chi. Now, but before we go to the plot, before we go to the animation I want to make the following statement. I have already said that at time pi by chi X of t shows a sudden change because this becomes 0. What happens when t is pi by chi? X of t becomes its original value. There is a revival and the Gaussian comes back to itself. If you look at X squared of t at t equals pi by 2 chi there are sudden jumps.

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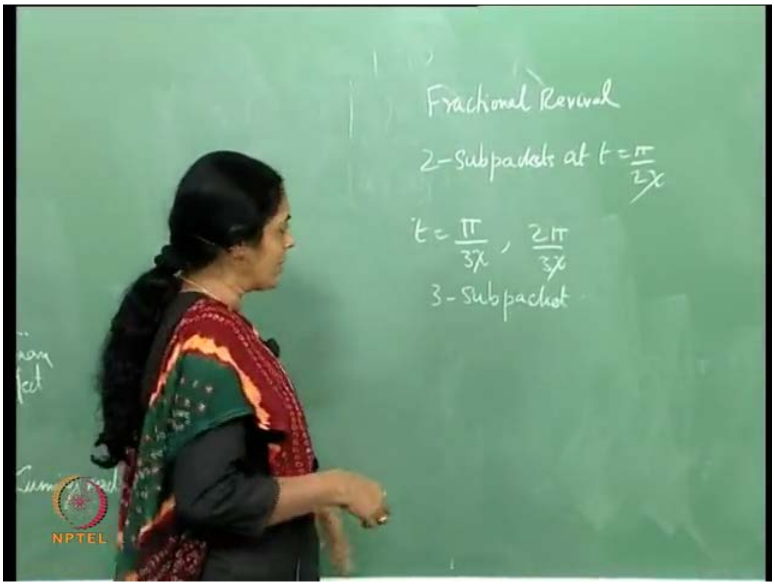


A phenomenon called fractional revivals occur, what is the fractional revival? Where the initial Gaussian splits into a superposition of 2 Gaussians, they are smaller in height. So, they are in a sense copies of the original Gaussian but not identical, you would call that a 2 sub packet fractional revival at t is pi by 2 chi. Similarly, a t is pi by 3 chi and 2 pi by 3 chi you will expect a 3 is sub packet fractional revival and so on because there will be 3 Gaussians and so on. So, it fractionally revives. It is a Gaussian form but not quite a reproduction of the original but you have 2 Gaussians here, 3 Gaussians here and so on superposed on each other. Revivals and fractional revivals are very interesting non classical effects. There are no counterparts and classical physics. I am showing this just to give you a feel for the kind of rich dynamics that quantum evolution can produce. So now, let us see.

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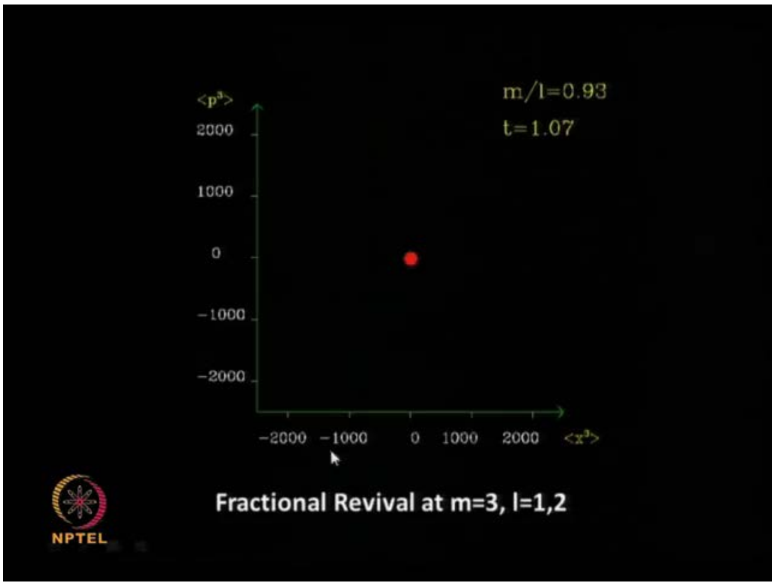


Now, this is a plot of delta X versus delta p. As you would see things did not move, it just stays still expect at the 2 sub packet fractional revival time when it moves. The same kind of thing can be seen if you look at X squared versus P squared. There is quiescence expect at that instant t is pi by 2 chi when you saw the red ball moving and again there.

Now, if you look at X cubed versus expectation P cubed, as I said it should happen at two instance of time, the oscillations and that is happening there. It moves and then there is quiescence. Did it twice and that is all. So, basically you find that for large nu, there are these sudden jumps at certain instance of time and you captured signatures of revivals and fractional revivals in observables. As you know quantum mechanics largely is about the study of observables, outcomes of experiments and these are interesting signatures of non classical behavior which you capture in observables. With this I have more or less concluded formally my set of lectures on introductory quantum mechanics.

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To quickly recapitulate these are the various topics that I handled. They were many modules. The 1st one was: operator methods, operator algebras. We looked at the angular momentum algebra also here without reference to arbitral angular momentum. But then we had linear vector space concepts: the Hilbert space and applications. So, the applications where: 2 and 3 level atoms angular momentum and so on. We examine the postulates of quantum mechanics. And then in this abstract language we studied the problem of the oscillator, the harmonic oscillator. I connected that up with quantum optics and to interesting superpose states of the radiation field like: the squeeze state, the coherent state and so on.

The next module was about functions of position and momentum. The wave function was introduced psi of X, its fourier transform cycled of X. Of course, this involved: understanding 1 dimensional potential well problems, redoing the simple harmonic oscillator problem in the language of the wave function, the hydrogen atom problem, the charge particle in a homogenous magnetic field and therefore, what you mean by a gauge choice.

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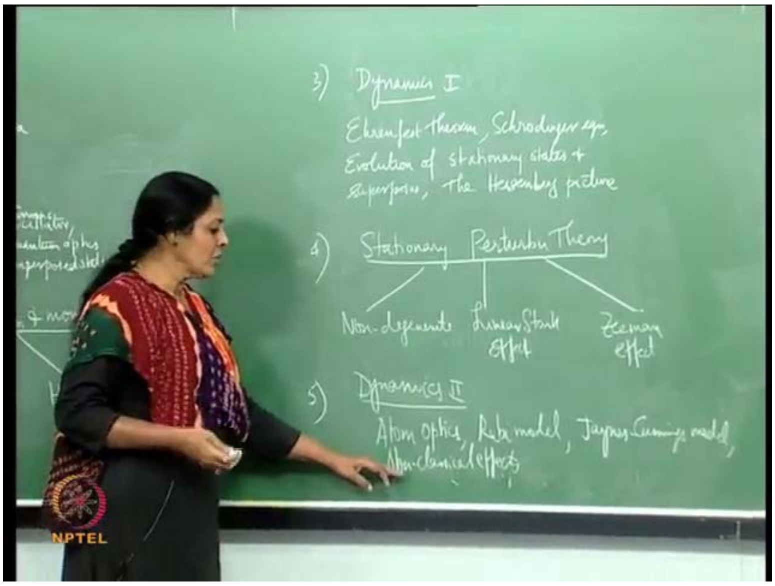


The 3rd module was what I call dynamics 1 where we looked at: the Ehrenfest theorem, the time independent Schrodinger equation, so evolution of stationary states and super positions states and also the alternative picture, the Heisenberg picture. We interrupted the dynamics by going over to an approximation method, a stationary perturbation theory where we looked at the non degenerate case. And then of course, the degenerate cases, linear stack effect and the Zeeman effect. Came back to dynamics 2 where I emphasized atom optics and tried to give you a sketch of a semi classical model of the radiation field interacting with the atom and then a fully quantum mechanical model.

Mentioning in passing about certain non classical effects, you already you know about squeezing I just mentioned things called revivals and fractional revivals. Throughout the course, I have attempted to take aspects of quantum optics along with the understanding of introductory quantum mechanics. And, I tried to show you how quantum superposition plays a very big role in certain interesting states of quantum optics.

I have interspersed my lectures working out certain problems like the quantum beam splitter and so on and illustrations of the Baker Campbell Hausdorff formula. Where ever possible I have used examples from nuclear and high energy physics. For instance, the shell model to illustrate the importance of the spin orbit coupling and charge independence of nuclear forces, the concepts of iso spin so on and so forth which is very followable at the level of introductory quantum mechanics and the tools that one use in introductory quantum mechanics.

With this, I conclude my lectures. I would not be doing a complete job of this unless I thank the members of n p tel who have supported me during this. My thanks are to due professor Mangal Sundar who is the coordinator of the n p tel program, Misses Usha Nagarajan who is the principle project officer, Mister Kannan Krishnamurthy who is the executive producer. And then coming to the video recording team itself I have to thank Mister Ravindranath for adjusting to various changes in my video scheduling, the excellent support given by Mister Ramachandran who is the project officer who led the video recording team, Miss Vidya, Mister Subhash, Mister Sabapathi, Mister Sridharan and Miss Pradeepa. It was very pleasant, people were very helpful, most accommodative and professional, good people to work with.

I thank you all.