Hello everyone my name is Shivam and welcome to my presentation on modeling Rabi oscillations.

Before we begin just wanted to give a quick outline for this presentation: We're going to start with an introduction where I talk about quantum optics, the lead up to the quantum dot which is the spontaneous parametric down conversion, and Rabi oscillations. Next we'll talk about the methodology of the problem and the resulting analysis that come from it and will wrap up with conclusions and future considerations as well as references and acknowledgements and now without further ado quantum optics.

So quantum optics is one of the most popular modes of implementation for quantum information processing and it is actually also one of the first and this is due to the high photon durability and the high mobility however it's also problematic for the same reasons because it's hard to generate entanglement when your photons are super fast or won't interact with anything so Knill, Laflamme, and Milburn implemented the KLM protocol in order to address this.

So we can actually summarize the KLM protocol with three main criteria one we need in tangling photon sources two we need high efficiency number resolving detectors in three we need complex optical circuits that exhibit both quantum and classical interference. In this project we will be focussing on the first criteria

So the industry standard for generating entangled photon pairs is currently spontaneous parametric down conversion and the basic process is there's an incident laser beam that's incident on a crystal and this beam is UN split into two constituent parts. The sum of the momentum and energy of the outputs is the same as the input, thus obeying conservation laws.

So while this is a wonderful, this is also a low efficiency process. In fact for every 10 to the six input photons we only get four output entangled pairs and while these outputs are guaranteed to be entangled. It occurs with very low probability so we need a replacement and a consideration for this is the quantum dot.

So outside of the name quantum dot if we were to consider the quantum nature of it we would look at entanglement but another thing we can look at is also rabi oscillations. The naive intuition behind the excitation of the quantum dot is that it would be a one and done process that it would be excited release a photon and that would be it but what we actually find is that it's cyclical instead and this re-excitation of electrons is actually fundamentally quantum process and was shown theoretically by Feranchuk and Leonov.

We can actually model rabi oscillations theoretically by considering a toy model of an atom excited electric by an electric field and this would be its hamiltonian so notice that we have a time dependent portion in the potential and a time independent portion as well and what we're going to do is we're going to solve it using the schroedinger equation which gives us the following results. If we then take these results and make some simplifications for example that were exciting it resonantly that we have an idea of what the potential looks like if we consider the effect of the electric field on atomic dipole and also taking an expectation value.

What we end up with is the following set of equations. Where we have the rabi oscillation as follows and electrons will oscillate at a frequency of Omega r / 2π.

So now that we understand what rabi oscillations are let's see if we can actually observe them at present we have no way to really observe electron dynamics however we do have a way to measure their emissions the photon so in order to understand how we model this we need to understand the statistical nature of a photon.

And for this we're going to consider another toy model so if we have a beam of light coming from a flashlight and we're going to say it has a length of L and suppose we divide that into end segments and we take that end all the way out to Infinity what we find is that not all the segments actually contain photons.

We can model this mathematically by considering the binomial distribution and if we use the following two approximations Stirling approximation and the binomial theorem.

What we end up with is the following equation and this is called a poisson distribution note the n bar this is the mean of the distribution. Poisson distributions are characterized by the mean which is unique to this distribution

We end up with three different regimes that are characterized by the relationship between the mean and the standard deviation. We’re going to consider the sub-Poissonian classification where the standard deviation is smaller than the square root of the mean. And in an idealized case there's a photon in every beam suggesting a standard deviation of zero and this would be akin to deterministic light.

So theoretically we've actually established that there is efficiency greater than spontaneous parametric down conversion so there are four classes of sub-poissonian light and our particular focus will be that where the atom actively takes energy from an external source IE the quantum dot.

So the quantum dot actually has a lot of benefits it has on-demand or deterministic generation of single photons like we talked about it has low multi photon emission so there is very low broadening it has high photon flux the ability to admit indistinguishable photons and numerous tuning mechanisms.

So how does it work? Well, if we consider the core-shell structure, it is a semiconductor coated by another substance the other substance must have a higher bandgap than the quantum dot and this creates a confining potential which then gives rise to a spectrum of bound states.

However before we continue I just wanted to clarify some of the language any solid is characterized with a valence band where the electrons are bound to the atom a conduction band where the electrons are excited to and are free and the band gap which is an intermediate section between the conduction and valence bands that has no electronic states upon excitation the electron moves into the conduction band and leaves behind an oppositely charged hole. And upon de-excitation the electron emits a photon and recombines with the whole with the whole this is called radiative recombination.

Now suppose we were to consider entanglement the quantum dot also produces entangled pairs. It does this by accessing a secondary excited state called the biexciton. using the biexciton exciton cascade. The biexciton l is a collection of two electron hole pairs which have opposing angular momentum and these undergo separate recombinations to create an entangled pair.

For further detail, the first recombination generates a right circularly polarized photon and the remaining electron hole pair. The next recombination generates a left circularly polarized photon the opposite can happen as well and we don't actually know which this results in the following bell state representation.

So the Reimer group uses a 2 photon resonant excitation scheme where if you were to use a single photon to excite the biexciton would violate the pauli exclusion principle as it has a net angular momentum of 0, while the photon has 1. so if you use two photons with opposing angular momentum and half the by exciton energy you would end up with an angular momentum of 0. And using a laser to do this makes the likelihood of this occurring very high. The group uses a 900 Ti sapphire laser with a wavelength of 894.0 nanometers and the biexciton emission is recorded to be at 800 94.6 nanometers and the exciton emission is at 893.3 nanometers.

So we've established the premise behind what we're measuring but we haven't actually put together a scheme to they have a model so there are multiple formalisms to describe a system in physics probably the most well known as the hamiltonian and at the results from a legendre transform of the lagrangian. And very basically this gives us the total energy of the system this formalism only considers the system however how do we actually include environmental effects well enter the lindblad master equation this considers a system the environment and the coupling mechanism between the two.

The general premise is that each component can be considered with its own unique Hilbert space. The total system would then just be the tensor product of the system environment and coupling mechanism however for simplicity we're going to write the environment and the coupling using the same basis of the quantum dot but still recognizing that they are unique hilbert spaces.

And considering this in quantum mechanics well we can start with the basic premise under the heisenberg picture and with the inclusion of the environment it would look up something like this and Li are your collapse operators and they represent the interaction between the system and the environment and gamma is the rate of spontaneous emission due to the collapse operators.

So now that we've established the backbone for completing this problem let's consider the actual problem itself so the PhD candidate Mateo Pena Kathy performed an experiment to detect rabi oscillations and this is what he found and in order to fit this model he used the following equation which was provided in mark fox is quantum optics. But he was hoping for a better fit and so he gave me the following.

He provided me with coherence and degree of time pin entanglement from quantum dots and this was written by Huber Ostermann Prilmuller Solomon Ritsch Weihs and Predojevic. As the title suggests this is time bin entanglement rather than polarization however the hamiltonian still applies as it is not specific to the entanglement mode.

And here in fact this is our hamiltonian that we're going to be using the Omega IR Rabat frequencies for the ground to buy exit on an the ground to exciton coupling in this case we're just going to make the two the same and call it the frequency of the laser. Delta X is the difference between the intermediate transition state and the exciton and delta B is the detuning due to the intermediate state between the ground and the biexciton. However, in this paper they claim that resonant excitation makes this 0.

Now that we have our hamiltonian we have to consider our collapse operators and these are going to be our collapse operators the first to collapse operators represent population decay due to spontaneous decay and the gammas represent rates of decay and the last two represent dephasing during transition and the gamma there is the rate of dephasing due to transition.

So in order to put all this together we needed some software because solving that analytically is a nightmare and I'm not paid enough to do it So what we use is Q-tip and we use the lindblad master equation in Q-tip it solves for the following expectation value.

And it does this with the following required parameters first we need the effective Hamiltonian, the initial state of the system, the gaussian pulse used to excite the system, a list of times to perform the actual calculations and finally a set of collapse operators which detail my dephasing.

Now this was all we had to do it wouldn't be much of a project we did actually run into three challenges here first our problem has three states the ground exciton and the biexciton rather than the usual two which are used for rabi oscillations. We needed to rewrite the operators so that it made sense to Q-tip. and finally we needed to change the incident pulse shape.

So to deal with our first challenge could we construct SU2 in terms of three by three matrices. put more simply can we actually make 3-D Pauli matrices and in fact, we can. we can do this by considering how raising and lowering operators act on 3D eigenstates.

And this leaves us with the following two raising and lowering operators.

Our next challenge was to write these operators in a way that was recognizable to Q-tip so in order to do this I considered material from doctor Bajcsy where he suggests the following translation transformation. if we consider the three-dimensional basis from challenge one we can actually get the following matrices.

Our last challenge was a little bit more tricky we use the gaussian pulse shape from Kevin fishers two photon interference tutorial however it resulted in the typical decay plot rather than Rabat oscillations and we also wanted to remain in a short pulse regime which is basically where the amplitude of the pulse is greater than the standard deviation.

So unfortunately I couldn't find any theory to help me with this, so I had to use the tried and tested trial and error method and I found that if the standard deviation was the same order of magnitude as the amplitude then we would have rabi oscillations.

And this leads us to the following effective hamiltonian where we see that the detuning between the by exit and in the ground state is given by 0.1 and the gaussian pulse used to excite the system is as follows note that these amplitude is on the same order of magnitude as the standard deviation.

What this gives us is rabi oscillations so we'll start with the ground state population it starts with 100 percent probability for occupation which makes sense because that’s how we calibrate the system. And we can see as the peaks diminish it oscillates at about 33.33% probability of occupation.

Next we have the exciton state population and this starts with 0% probability for occupation which makes sense as there will be none until excitation. It has an initial peak at T not at 45% occupation probability which is representative of not wanting directly excite and exciton however it may still happen due to real life. And as peaks diminish again this oscillates at about 33.33% probability for occupation.

Finally we have the biexciton and it starts again at 0% probability for excitation and we have a High Peak of occupation probability at 90% and this is representative of wanting to directly excite the biexciton population and again as peaks diminish this oscillates at about 33.33% probability of occupation.

And with these results and with these results we can make the following conclusions first rabi oscillations are indeed quantum a quantum effect due to the electron re population 2 while we cannot directly study electrons we can study the photons instead and if we consider photons the statistical nature of photons leads us to the possibility of a deterministic source a sub Poissonian source. and that's up ausonian source is the quantum dot the framework used to represent all of this will have to consider environmental effects and that's why we use the lindblad master equation.

In order to put all of this together we can use a package in Python called keytip an there were three main challenges to implement it we were using A3 dimensional system instead of a 2D1 we needed to convert it to a language that made sense to Python an we needed to change the gaussian pulse to detect rabi oscillations and with all of this in consideration we actually found Ravi oscillations in all three states of the quantum dot which is exciting.

However the story doesn't end here Q-tip uses natural units Anna such I didn't implement the reimer group parameters because I wasn't entirely sure about how I was going to go about this and without implementing these parameters I couldn't actually compare it to what Mateo got next our order of magnitude difference between the intensity and the standard deviation is not necessarily indicative of a short pulse regime and finally matteo's models used pulse area rather than time on the X axis and I was unsure of how to translate this model to consider pulse area instead. so I can't safely conclude that the quantum dot is a quantum system however I can say that we are on the right track.

I'd like to acknowledge Dr. Reimer for your guidance and supervision I couldn't have done this without you and I can comfortably now say that I know how to read research papers and implement a solve problem solving scheme to solve problems the QPDL group you let me participate in group meetings despite not being very knowledgeable and your feedback was invaluable I learned so so much. Mateo Pennacchietti and Sonell Malik for your guidance and support when I felt like I was stuck which was unfortunately a lot and my husband friends and family and everyone else in the background I would not be anywhere without any of you.

Here are my references

and Thank you all for attending my presentation.