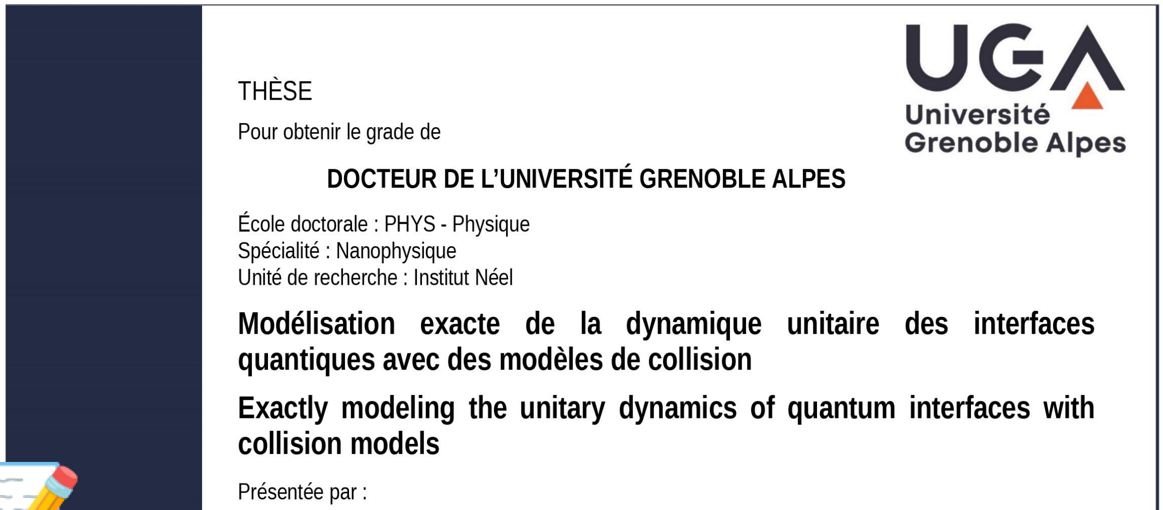

THÈSE

Pour obtenir le grade de

DOCTEUR DE L'UNIVERSITÉ GRENOBLE ALPES

École doctorale : PHYS - Physique
Spécialité : Nanophysique
Unité de recherche : Institut Néel

Modélisation exacte de la dynamique unitaire des interfaces quantiques avec des modèles de collision

Exactly modeling the unitary dynamics of quantum interfaces with collision models

Présentée par :

Defense presentation

Slide 1: General introduction (30s)

Good morning everyone, I'm Bruno Ortega Goes and today I'll be presenting the work I did in the last 3 years at Institute Néel, in the doctoral program of University of Grenoble Alpes under the supervision of professor Alexia Auffèves.

My thesis is entitled "Exactly modeling the unitary dynamics of quantum interfaces with collision models", and it received founding from the project Qudoth-tech, a Marie Curie action.

Slide 2: Positioning and motivation (1min)

When I refer to a quantum interface I'm thinking about the transfer of information between light and matter through their interaction. Such interfaces are ubiquitous to build a quantum network or memory based quantum repeaters, where we have stationary qubits located in the nodes and light playing the role of a flying qubit, that's to say, it is responsible for the transfer of information between the nodes.

Artificial atoms are engineered systems that behave just like natural atoms: they posses discrete energy levels, being able to emit single photons. One advantage of such systems is that they can be coupled with waveguides, for instance, prooviding easy integration in several platforms.

In the solid state we can mention Quantum dots that are formed between layers of materials with different lattice parameters. Such systems have proven themselves to be excelent single photon sources, specially due to the possibility of building micropillars around it. Moreover, they can be dopped with single electrons or holes (charge carriers), making them suited for quantum communication and to build the resources states for measurement based quantum computing that I'll briefly discuss in the end.

Slide 3: Scope of the thesis (50s)

In my work I was concerned with both, fundamental research and technological applications.

On the fundamental side I studied the emergence of non-classical features of a field that is scattered by a quantum emitter. This is discussed in chapter 3 of my thesis and is not going to be presented today. I also studied how to perform I non-destructive measurement of a spin in a quantum dot. Then, on the technological side I studied the possibility of performing a photon-photon gate and made a throughout error analysis of the coherent errors present. Finally I modeled experiments that implements a protocol to generate photonic entangled states.

All of this study is done within the quantum measurement background and the basis of all the studied is the collisional model, a powerful theoretical tool that provides full information about the entangled state of light and matter.

Slide 4: Let's jump into the von Neumann measurement model, so we can all be on the same page about the background. (10s)

Slide 5: How can we measure the state of a qubit? (40s)

To grasp the main idea of the von Neumann measurement model and motivate the use of the collisional model I want to discuss a concrete simple example. It goes as follows:

I have at my disposition a single bosonic mode, initially in the vacuum state, that will be the system I use to **probe** a **qubit** that is actually the system I want to obtain information about, hence my **target**.

The target is initially in a balanced superposition of its possible states, here up and down. The joint initial state of the system and meter is initially a product. So how can I mesure the state of the qubit?

Slide 6: Pre-measurement is the process that generates entanglement between the target and probe. (55s)

Firstly, I put the to systems to interact with some strength g_0 with an interaction Hamiltonian H_{SM}.

Here my interaction Hamiltonian is proportional to σ_z and to $a^\dagger - a \propto p$, the momentum. We can easily solve the Schrödinger equation and obtain the entangled state at everytime t.

Here, we observe that each eigenstate of σ_z (up and down) is entangled with a bosonic state $|\psi_{\uparrow(\downarrow)}\rangle$, the **pointer states,** because they "point" in which eigenstate the target is**.**

In our case, the pointer state are the displaced vacuum, or a coherent state, with amplitude proportional to the product of the strength of the interaction, the time of interaction and the respective eigenstate $\pm g_0 t/2$.

That means that the spin down displaces the vacuum to the left of the real line and spin up displaces to the right.

The process of generation of entanglement between the target and the meter is dubbed **pre-measurement.**

Slide 7: Measurement happens when the state of the meter is collapsed with a classical apparatus. (30s)

After interacting for a while we come with a classical apparatus and measure the state of the meter. This will cause a **collapse** of the state of the meter and at this point we say that the **measurement** happens.

Let's suppose that we projected the state $|\psi_\uparrow\rangle$, this leads to the following probability amplitude:

$$\langle\psi_\uparrow|\Psi_{SM}(t)\rangle = \left(\frac{|\uparrow\rangle_S + |\downarrow\rangle_S \textcolor{red}{\langle\psi_\uparrow|\psi_\downarrow\rangle_M}}{\sqrt{2}}\right)$$

And we can **infer** the qubit is in state up if the overlap highlighted in red vanish! When this happens we say that **all information about the target is encoded in the meter.**

Slide 8: How to quantify the quality of the pre- and collapse steps? (1min30)

Here, we present the figures of merit we'll use throughout this presentation the quantum and classical **Bhattacharyya coefficients** (qBhat and cBhat), they quantify the quality of the pre- measurement and collapse respectively.

The qBhat is simply the modulus of the overlap of the pointer states. The more orthogonal they are the more information about the system is encoded in the meter, the better is the entanglement. They are directly related to the off-diagonal (coherence) terms of the target's density matrix.

It is represented in the plot by the solid black line, we observe it goes to zero, if we look at the lower panel of the inset we have a representation of the density matrix of the target. The red squares shows it is initially completly populated and as time goes by the off-diagonal terms wash away, becoming yellow.

The cBhat quantifies how disjoint are the probability distributions of the measurement. It does so by taking the set of possible outcome $x \in \mathcal{X}$ and multiplying the conditional probability that the outcome x is obtained given that the state is l or m. It is represented by the dashed red line in the plot, and we can see the Q-function (a probability distribution for a particular type of continuous variable measurement) which shows the field initially in the vacuum state and as time passes we observe the appearence of two blobs associated with spin up and down.

Importantly, the qBhat is a lower bound for the cBhat!

Slide 9: Transition to Collisional model or how to close open systems (30s)

Now, that we have the background in mind I hope it is clear that **having the wave-function is extremely important when measurement is concerned**, not only it contains full information about the dynamics of the system but it also allows us to compute our figure of merits. This is the point where the collisional model comes in!

Slide 10: Qubit + multimode electromagnetic field in a 1D waveguide (55s)

Now let's consider the following situation. We have an emitter with ground an excited states positioned at position $x = 0$, interacting with a multimode wave-guide with some strength g_0. Each system has this bare Hamiltonians and they interact via a Jeynes-Cummings type of interaction.

Note that the emitter interacts with **all the modes,** represented by the wavevector k **at the same time**. The multimode caracter of this problem poses a big problem in solving the joint dynamics. Standard approachs include "not caring" about the wavefunction of the waveguide, we consider it as a "bath", trace over it and study the open system dynamics of the target only. The other approach is considering just a single mode, as in cavity QED. Also, we may obtain information about the input and output fields using the Heisenberg picture. But **that's not what we want!** We want all information we can have and this is contained in the wavefunction.

Slide 11: Interaction picture & time discretization (30s)

To attack this problem we use a trick:

1) we move to interaction picture with respect to the bare Hamiltonians, and

2) Follwing Mark Kac's moto "be wise, discretize" we discretize time .

This allows us to define what are rigorously "spatial bosonic operators", as the (discrete) Fourier transform of the wave-vectors k. As it only depends on the temporal parameter I'll refer to it as *bosonic temporal mode.*

Slide 12: Interaction picture & time discretization (30s)

In this scenario the interaction happens locally at time t_n in a repeated, sequential fashion. An input mode comes from the right, interacts with the qubit for a short time and it leaves to the left, as the output bosonic mode. This can be viewed as a series of collisions between the emitter and the temporal modes, hence the *Collisional model interpretation.*

Slide 13: Interaction picture & time discretization (45s)

This is great because now we can use the Suzuki-Trotter formula and obtain the joint `emitter+field` wave-function at any time by repeatedly applying the evolution operator to a given initial state $|\Psi_0\rangle$.

Of course, it might be hard to find a pattern and to write down a general solution, but we do have a method to find it!

As a sanity check of the procedure, we remark that this procedure leads to an input-output relation for the average values of the input-output fields and the fluorescence of the emitter (showed by the lowering operator) which is similar to the well-known textbook relation obtained in Heisenberg picture for the operators by Gardiner Collet.

Slide 14: Coherent field solution (50s)

Now that we have this let's consider there is initially a coherent field in the waveguide, and the qubit is in any of its energy states. We write these guys in the temporal modes obtaining an initially uncorralated field (as a technical remark this leads to a markovian dynamics, and the reduced dynamics of the qubit is dictated by a Lindblad master equation).

We go to a displaced reference frame and we can obtain the entangled state as follows:

$$|\Psi_{\beta}^{\zeta}(t_N)\rangle = \sqrt{P_g(t)}|g\rangle|\phi_g(t)\rangle + \sqrt{P_e(t)}|e\rangle|\phi_e(t)\rangle$$

where the pointer states are given by:

$$|\phi_{\varepsilon}\rangle = \frac{1}{\sqrt{P_{\varepsilon}(t)}}\left[\sqrt{p_{0,\varepsilon}}\tilde{f}_{\varepsilon,\zeta}^{(0)}(t) + \sum_{m=1}^{\infty}\sqrt{p_{m,\varepsilon}(t)}\int_0^t d\mathbf{s}_m \tilde{f}_{\varepsilon,\zeta}^{(m)}(t,\mathbf{s})\prod_{i=1}^{m} b_m^{\dagger}\right]|\emptyset\rangle$$

where $\tilde{f}_{\epsilon,\zeta}^{\text{number of emitted photons}}$ is the coefficient given the amplitude of probability of having a emission of m photons during the target's evolution from the state zeta to episilon.

> ✅ In the end the solution boils down to finding these coefficients, which can be done analytically!

Slide 15: Single photon solution (50s)

Now, let's assume we shine a single photon on the emitter. It has a noralized temporal shape $\xi(t_n)$. The first different we remark with the coherent pulse is that it is already correlated initially in the temporal basis, leading to a non-markovian dynamics.

We find the expression for the joint wave-function as follows **(point to the equation).** Of course it has at most one excitation, as it must be due to the JC interaction. When the qubit is in the ground state we have an interesting thing happening:

> ✅ In blue we observe the part of the field that has already interacted, hence the scattered field has a different temporal shape.

> ✅ In red we have the modes that **have not yet** interacted, possessing the initial temporal shape.

This is an important and crucial remark for what is to come!

> 🚨 Up to this point it should be around 10-15 minutes. Not more!

💧Transition slide: Now we have all the ingredients on the table to discuss some of the main results! We start with the “Energy efficient entanglement generation and readout in a spin-photon interface” (15s)

Slide 17: Measuring the spin state (1min5s)

To be concrete, we consider the following set-up: we have a quantum dot doped with a single electron. This introduces a spin degree of freedom and **optical selection rules.** The spin up can be excited to a trion up (a spin singlet and a hole) with right polarized light and spin down gets excited to trion down with left polarized light. This is due to the conservation of angular momentum.

We restrict our energy budget to one quanta (one photon) at most. This is the heart of the study. With this restriction we compare two types of fields, i.e., we’ll shine light with different characteristics in the QD:

1. A (low energy) coherent field with at most one photon in average. This has a poissonian distribution, so I’ll refer to it as a classical light, and
2. A superposition of vacuum and a single photon.

❓ The questions are: which one entangles better? We'll measure it using the qbhat and does a better entanglement translate into a better readout? This requires designing a good experiment and we'll study the cBhat.

Slide 18: Spin-light entanglement (55s)

Now, I present the pointer states associated with the coherent and the superposition of vacuum and a single photon. Both have at most a single **horizontally polarized photon.** That is necessary in order to trigger both transitions (up and down).

We are considering the long-time limit, in which the 4LS has already decayed.

Observe that the classical state, the pointer states associated with up and down emit only right and left polarized light, respectively. In the case of the single photon, the pointer state up has a component R that is associated with the part that has been scattered with a temporal shape $\Upsilon(t)$ **but also have a L component that stems from the part that has not yet interacted and holds the temporal shape $\beta(t)$. This is the main difference between the pointer state. Let's check how it affects the qbhat.**

Slide 19: Spin-light entanglement (35s)

The qBhat of the classical light becomes a constant value, called p_0 that is the probability of no photon re-emission. This is the vacuum component of the scattered coherent state which gives a **fundamental** limitation to the entanglement generated. In the image we observe graphically the vacuum component of a coherent state with an average of one photon.

The qBhat for the quantum state on the other side **can become zero for any input temporal shape** $\beta(t)$ by correctly tuning the single photon probability p_H.

Slide 20: Quantum advantage: the superposition of number states creates orthogonal pointer states of the meter. (40s)

Now I showcase this for the case of decreasing exponential. On the left we can see that the qBhat for the coherent field **never vanishes** in the low energy sector, for any bandwidth.Note that the y-axis we go from short bandwidths, i.e. long-pulses to short bandwidths, very fast short pulses.

On the right we observe that provided that at least we have the probability $p_H = 1/2$ we have a vanishing qBhat, represented by the white line.

> ❗ Bam! We have a quantum advantage because quantum light can create orthogonal pointer states and classical light cannot. Hence, quantum light entangles better!

Slide 21: Phase measurement (2 min)

Ok, but does it mean that at the we can extract all this information from the target with our meter? Well, it depends on the regime we are. For long pulses the information is mostly encoded in the phase, while for short pulses it will be encoded in the polarization. And in between, the information is spread in temporal modes, and the analysis is more complicated.

As the polarization is already widely used in the community, we propose a scheme that works for long pulses, the (quasi) monochromatic regime.

We consider we have a source of R-polarized light, a single photon if quantum and a coherent field with an average of one photon if classical. The light passes by a Beam splitter. Part of it will interact with the QD that has the spin prepared in up or down and the other part is reflected by a mirror, the phase plate only optimizes the probability of a click in the detector if the spin is up and make it 0 if it is down. We have the following map in this regime **(refer to the map)**.

Now we can compute the following:

1. qBhat for the classical state: represented by the red line. As the bandwidth becomes shorter it goes to a plateau, the vacuum probability component. Since the qBhat is a lower bound for the cBhat, the cBhat of the classical state cannot be better than that.
2. qBhat for the quantum state: represented by the black solid line. This goes to zero as the bandwidth is shorter.
3. cBhat for the classical state: we observe that when the bandwidth is shorter than 0.1 it goes below the red dashed line. Bam! This region (1) defines where we have a better read-out over by using the quantum light over the classical light. Quantum advantage at the classical level. The region 2 the advantage is unclear, as I briefly

mentioned, there might be a better measurement scheme that targets other degrees of freedom leading to some advantage. Region (3) is below the qBhat for the quantum state, hence it is unnaccessible.

With this we conclude this first part where we obtained a quantum advantage in both pre-measurement and collapse (by correctly designing the experiment).

💧 Transition slide: Now that the fundamental was studied, let's dive into our first technological application. I wanna show how we can make a photon-photon controlled phase gate with this device and study the coherent error it is subjected to. (15s)

Slide 24: C-Phase gate and Error (50s)

To propose the c-phase gate we consider the single rail basis. This basis maps the presence of a R-photon or its absence as the logical qubit. Vacuum is the logical 0 and a single R-photon is the logical 1.

We have the following map saying that vacuum doesn't change, an R-photon doesn't interact with the spin and when the spin is up the scattered photon gains a phase π and, **due to the finite duration of the pulse** it gets its shape deformed, represented by the tilde. For long pulses, the (quasi)monochromatic regime we have only the phase appearing.

Importantly, if we consider the ideal scenario, without decoherence of the spin or photon losses the sole source of error is the finite duration of the pulse, that is what the experimenter really sends.

Slide 25: Leakage out of the logical basis due to pulse finite duration (40s)

We will characterize this coherent error. The protocol is designed to work in the quasi-monochromatic regime (indicated by the blue star) with quantum light. We want to understand the finite duration of the pulse will affect the performance. I'll define a parameter m tilde that quantifies it.

For the moment, I not that the output photon R tilde can be decomposed as a component perpendicular to the logical basis and a component that is in the basis.

This way we observe that there is a leakage out of the logical basis that will the the source of error.

Slide 26: Quantifying the non-monochromaticity (52s)

I define the parameter m tilde as the projection of R tilde in the basis element R of the logical basis.

From the collisional model we know that an inpiut field R with temporal shape beta is scattered with a change in the temporal shape that becomes upsilon.

This allows us to write m tilde as a function of the input and output shapes of the wavepackets. This is a nice equation, since it makes the brigde between the leakage of information out of our logical basis and the system parameters (pulse bandwidth, vacuum decay rate).

Here we observe to instance where the pulse is monochromatic in (a), observe that the input and output are basically the same shape and in (b) we have a non-monochromatic output.

Finally we see how the parameter goes to 0 as the bandwidth increases, that means that all information leaked out.

Slide 27: Gate protocol (50s)

The protocol goes as follows:

I assume the 4LS is initially prepared with spin up and I'll use two pulses that are a balanced superposition of vacuum and a single photon **(refer to the bottom left corner of the slide).** I'll also use 3 rotations (instantaneous) around the y-axis. The first initializes the spin in the + state and the last erases spin information.

So the protocol is, apply a rotation, send the first pulse, apply a second rotation, send the second pulse, apply the last rotation and make a measurement of the spin state. Decoupling the spin state will leave us with a photonic state that can be written as the action of a gate G conditioned on the spin outcome j.

Slide 28: Gate action (50s)

Now let's a look at the gates implemented for each of the outcomes and the coherent errors associated with it.

In the ideal case we have a controlled phase gate for both outcomes, for spin up we have 01 going to -01 and for spin down, apart from a global phase we have 11 going to -11. If the pulse is finite though, meaning m tilde is different from one we have some coherent errors, associated to an imperfect rotation, by some angles episilon up and down and an angle delta (remember, this is associated with the information leakage).

We can quantify the error with the average gate fidelity, but it only provides a number, and doesn't give a clue about the error characterization itself. **(Move to next slide)**

Slide 29: Error matrix (55s)

So in order to fully characterize the error we use a tool colled the error matrix. It is motivated by making the remark that the real imperfect gate can be written as a composition where we have the ideal gate composed with some error.

Since the ideal gate is reversible, we can invert it and obtain the error matrix.

Now we need a model to grab all the possible errors that occur. For that we use the Pauli error model, in which each Pauli matrix models one type of error. The identity informs no error occured, the sigma x heralds a bit flip, the sigma y models a bit and phase flip and the sigma z highlights a phase error.

We obtain the analytical form of the error matrix and decompose it in a 2 qubit Pauli basis. **(Move to next slide)**

Slide 30: Error matrices: Hinton diagram (54 s)

Looking at the matrices, for spin up on the upper panel and spin down in the lower we observe that when m tilde is 1 we just have one element on the top left corner, associated with the identity matrices in both qubits, hence telling us that no error occured. As a technical remark, this element is associated with the gate (process) fidelity.

For an imperfect process we oobserve the appearence of the elements associated with the phase error in both qubits, moreover the bottom right element informs that the errors are correlated, meaning that if a phase error occurs in the first qubit, it also occurs in the second. Finally, for spin up the phase error associated with the first and second qubits is symmetrical, while for spin down they are not, this is a consequence of the assymetry of the interaction of R-photons with spin down and up.

💧 Transition slide: This concludes the 1st technological application where I showed how a photon-photon gate can be implemented and the coherent error characterized. Now let's go to

the final part, in which I want to discuss the SPI under the influence of a magnetic field. (15s)

Slide 32: SPI under a magnetic field (40s)

We consider the same set-up as before but now we add a *weak* magnetic field along the x-direction, i.e., perpendicular to the quantization axis of the QD. When I say “weak” it means that it is not strong enough to cause a relevant Zeeman splitting, so the

The magnetic field causes the spin to rotate, in a finite amount of time (not instantaneous as I considered before).

This is a set up used to implement a protocol proposed by Lindner and Rudolph with the goal to generate a highly photonic entangled state, known as “cluster states”.

Slide 32: What is the LRP and how does it work? (30s)

The LRP goes similarly as follows: we initialize the electron spin in one of its states and then we apply a Hadamard gate and a pulse, a gate and a pulse. In the end we have a linear entangled state compose of N photons and the spin. The spin is decoupled by measuring the last emitted photon what leaves us with a cluster state composed of N-1 photons. Now, how is it implemented in the lab?

Slide 33: Experimental implementation (1m40s)

In C2N the group levarage a LA phonon assisted excitation scheme to be able to measure the last emitted photon by filtering the input laser, this is accomplishedbecause they send a slighly blue-detuned laser. They are able to populate the trion state with high fidelity.

Then we start considering the experimental impeerfections that can be considered in our clos

The first important thing is that once the state is prepared in trion up, for instance we want that the decay happens much faster than it has time to rotate, emitting a R-photon an initializing the protocol in the spin down. So, we want the ratio between the Larmor frequency in the excited state and the decay rate to be much smaller than one.

Then, due to the different particles concerned, electrons and holes have different Larmor frequencies, they couple differently to the magnetic field. So there is also a ratio between the Larmor frequency in the ground and the excited state. Finally, the excited state (trion) only interacts with the external magnetic field, so it’s controllable, while the ground state, the electron spin, is also affected by *parasitic fields.* For instance, the Overhauser field that is created by the nuclei surrounding the quantum dot. It adds to the external magnetic field tilting its direction, which points in a direction n_g instead of the desired x.

Hence, the protocol we just discussed works in the following ideal scenario:

1. The ratio between Omega and gamma is much smaller than 1
2. The Larmor frequencies are the same, hence r_ge is one, and
3. When in the ground state the magnetic field points to the x direction, so the inner product between the vectors n_g and x hat must be one.

Slide 34: Spontaneous emission solution (40s)

We include all these parameters in the model with a sligth change of notation **(refer to the red box)** and we obtain the wave-function at any time t for the spin initially in zeta.

Let’s look at the fourth line to interpret it. It says the electronic spin state is up and there was a L-photon emission event.

In the integral we have a rotation from the spin zeta to spin down during a time “u”, then a L-photon is emitted leaving the system in the ground state with spin down an it rotates under the magnetic field until it ends in the spin up.

Slide 36: The model fits experimental results. (35s)

To test the accuracy of the model we fitted experimental data provided by the authors of reference 3 where the hole dynamics is studied under different magnetic field. We observe that the intensities as well as the degree of circular polarization data, represent by the points, matches the theoretical prediction, represented by the black dashed lines.

This is an important sanity check of the model, and provides a solid ground for the studies to come.

Slide 37: What is the impact of deviations from the ideal scenario to the fidelity? (35s)

Assume we a click of a R-photon in the detector, this heralds that the electron spin (in the ground state) is up. Now we’ll leave it make a pi-two rotation and it should go to the target state minus i. In the idel scenario. If this is not the case, then we have that the spin goes to a real state represented by the pink arrow. We are going to study the fidelity, which can be obtained analytically with our model.

Slide 38: Fidelity analysis: impact of finite pulse duration r Omage gamma and different precession frequencies r ge (30s)

Let’s assume there are just the imperfect ratios for the moment, and that the magnetic field is perfectly aligned.

> ❗ In this case we observe a high fidelity overall, and that the quantity that impacts more this figure of merit is the ratio Omage gamma.

Looking at the red line that demarks the equal Larmor frequencies, we see that the fidelity is demished as the Omaga (and hence the magnetic field) increases.

Slide 39: Fidelity analysis for different r ge: impact of finite decay r Omega gamma and imperfect alignment of the magnetic field inner product n g and x hat (50s)

Now we look how the imperfect alignement affects the protocol as a functin of r Omega gamma and for different fixed values of r ge.

Here we see that the closer we are to the ideal alignment the better the fidelity in all three instances. However, as the ratio r ge increases, and 2.5 is the closer to the experimental situation we observe a “shrinking” of the high fidelity region.

This closed dynamics approach gives insights on:

1. How each imperfection affects the fidelity of the first step of the protocol, and hence the quality of the generated cluster state.
2. Which set of parameters will provide the best fidelity.

Moreover, we can also study the photonic state itself and the fidelity of the generated cluster state.

💧 Transition slide: I reach the end of this presentation, and I want to wrap up the conclusions and provide some perspectives. (10s)

Slide 41: Conclusions (50s)

So in this thesis, within the quantum measurement background I exploited the collisional model technic to “close” open quantum systems, taking advantage of the fact that it provides full information about the light-matter wave-function.

This allowed me to investigate both fundamental and technological applications of quantum mechanics.

I studied and probed a quantum advantage in the pre-measurement and collapse step of a non-destructive measurement of the spin in a spin photon interface.

Then, I used this results to design a photon-photon gate that used the spin as the non-linear entity promoting the interaction between the photons and made a through error analysis due to pulse finite duration.

Finally, I used this technique to model a state-of-art experiment that generates a linear cluster state, considering the most fundamental imperfections, and studied the impact on the fidelity of the target spin state.

Slide 41: Perspectives (30s)

We can envision now spin-spin entaglement, I mean, the generation of entanglement between twoo nodes by using the output field of one photon as the input of another node.

We can study protocols to generate non-classical states of light, within this type of paradigm.

And, oon a fundamental side the collisional model and quantum optics settings can be used to further study both, theoretically and experimentally, the laws of thermodynamics extended to quantum scenarios.

Slide 42: Publications (33s)

During these 3 years I co-authored 3 published papers, the first we investigated non-classical features of the scattered field, it is part of the thesis but wasn’t discussed here due to time restrictions. This is a PRA.

The part of the non-demolition measurement discussed today was published in an open journal, quantum and finally, the paper that inspired the theoretical modeling discussed in the end of this presentation where high fidelity cluster states was generated. This is a nature photonics.

Slide 43: Participation in events (10s)

I also had the privilege to participate in several events and schools where I discussed with other researchers and presented posters or talks.

💧 Thank you all for your attention! The members of the jury that are present, and the ones that are in visio as well as my colleagues who are in Singapoure watching it, and everyone present here today. (15s)

Total: 2024s = 34 minutos (idealmente, isso é o tempo de leitura apenas)

The timing of eah slide was estimated with: https://niram.org/read/ and I added 10 or 5 seconds more to each (just adding a bias!).