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Tēnā koe. Ko Hākopa Ngaha tōku ingoa, nō Tāmaki Makaurau i Aotearoa ahau. My name is Jacob Ngaha, and I am from Auckland. New Zealand. I am a postdoctoral research fellow in the Department of Mathematics at the University of Auckland (UoA). My research background is primarily in theoretical quantum optics, in particular, cavity electrodynamics (QED) and the theory of open quantum systems. During my MSc (Master of Science) and Doctor of Philosophy (PhD), I worked with Howard Carmichael and Scott Parkins at UoA. My current research is in the applied mathematics field of nonlinear dynamics, focusing on the dynamics of nonlinear photonic systems.

The structure of this research statement is as follows: I begin by discussing my MSc and PhD research projects; I then introduce my current research as a postdoctoral fellow; and finally, I discuss some of the future projects and research ideas I will continue to pursue.

Two-Photon Resonance Fluorescence of a Three-Level Ladder-Type Atom

My MSc project focused on the fluorescence spectrum and photon correlations of a three-level ladder-type atom when driven at two-photon resonance. This project came about following correspondence between Howard and Andreas Wallraff's group at ETH Zurich. The Wallraff group had conducted experiments on an artificial atom in a circuit quantum electrodynamics (QED) setting, and I was tasked with interpreting the results from a real-atom perspective.

Due to the ladder-type structure of the energy levels, the atom de-excites via a two-photon cascaded process: from the upper level to the middle, and then from the middle level to the lower. At weak driving amplitudes, this behaviour manifests as two distinct peaks in the incoherent power spectrum corresponding to each bare state transition. At strong driving amplitudes, however, the degeneracy of the atomic dressed states is lifted, introducing up to twelve allowed cascaded decay paths with seven distinct peaks appearing in the power spectrum.

To further investigate the dressed state picture of the fluorescence spectrum, I turned my attention towards the photon correlations of each frequency component. To achieve this, I modelled a cavity-based frequency filter to calculate frequency-filtered second-order correlation functions. Using a cascaded open quantum systems theory approach, the fluorescence was cascaded into a tuneable single-mode cavity, correlating the output field of the cavity mode. I computed frequency-filtered auto- and cross-correlations for combinations of each of the different frequency components. The resulting antibunching, bunching, and second-order coherence indeed verified the dressed-state cascaded structure I derived.

Since the MSc, I have taken the analysis a step further. By making a secular approximation and rewriting the Lindblad master equation in a dressed-state basis, I have derived analytic expressions for the second-order auto- and cross-correlation functions for each of the dressed-state transitions. When compared against the frequency-filtered correlations, there is close agreement with the dressed-state cascaded structure.

Frequency-Filtered Photon Correlations

Near the end of the MSc project, I found that the standard single-mode cavity approach was not sufficiently effective as a frequency filter. The Lorentzian profile of the frequency response resulted in far-reaching wings; hence, there is always a trade-off between linewidth – and, therefore, frequency isolation – and temporal response. This naturally led on to the topic of my PhD research: frequency-filtered photon correlations.

In order to address this trade-off, I took inspiration from an ideal filter: a sinc – or rectangular – filter. Unfortunately, sinc filters are non-causal and thus non-physical. Even though this was a theoretical project, it was important that this filter model be physically realisable, therefore I decided to continue working with cavity-mode based frequency filters.

I found that by coupling an input field into an *array* of single-mode cavities – rather than a solitary cavity – the temporal response resembled that of a positive-sided sinc function. The frequency response of this *multi-mode array filter* model is approximately rectangular, with much sharper cut-offs in its response when compared with a standard Lorentzian. This allows for much wider filter bandwidths, and therefore a faster temporal resolution, without sacrificing the frequency isolation of the filter.

I applied this model to two atomic systems to test its efficacy: a resonantly driven two-level atom and the three-level ladder-type atom of my MSc project. In both systems, the multi-mode array filter was able to accurately capture the auto- and cross-correlations as derived in the ideal, secular approximation. The improved frequency isolation also opened up some questions on the effect that frequency filtering has on measured photon correlations.

Phase Resetting in the Yamada Model of a *Q*-Switched Laser

My current research as a postdoctoral fellow is in theoretical nonlinear photonics, where I am studying *phase resetting* in the Yamada model of a semiconductor laser with a lossy saturable absorber.

A *Q*-switched laser exhibits strong, stable intensity pulses. In a dynamical systems setting, these are manifested as stable, attracting periodic solutions. An induced, external perturbation will have some effect on how the system returns – or resets – to the stable periodic solution; in particular, there will be an induced phase shift relative to the unperturbed oscillations. Using numerical continuation methods, I am studying how these phase shifts are affected by the "direction" and size of the perturbation, i.e., a perturbation in the gain, absorption, intensity, or some combination of all, and how strongly we are perturbing the system.

Phase resetting was first used in mathematical biology to study the effect of perturbations on firing neurons; however this is the first time it has been applied to an optical system. While the Yamada model is a relatively simple system, we can apply the same phase resetting tools to more complex optical systems.

Future Work

There are two main avenues of work that I wish to pursue further.

The first is to further investigate the effects of frequency filtering on the photon correlations of the filtered three-level atom. In the frequency-filtered photon correlations, I found similar destructive interference in the cross-correlations to the work of Schrama et al. [in Phys. Rev. A **45**, 8045 (1992)]. I will take a similar approach for the three-level atom.

The second is to study different configurations of the multi-mode array filter. The configuration I modelled consisted of an array of tuneable single-mode cavities in parallel, where the input field passes through an array of beam splitters. With the recent advances in on-chip photonics, another possible configuration is an array of on-chip microring resonators, such as the work of Chen et al. [in Nanophotonics **12**(4), 715 (2023)]. This configuration can be studied by taking a quantum mechanical approach, as well as a transfer matrix approach for the input and output fields.

I am also currently working on publications on the results of the frequency-filtered three-level atom and the phase resetting results from my current research.

Summary

To summarise, my main research interests are cavity QED and atomic interactions. Through my MSc and PhD research projects, I have built a strong foundation in the theory of open quantum systems and acquired the necessary skills to model quantum optical interactions. Furthermore, my transition from theoretical quantum optics to nonlinear dynamics has broadened my technical skill set, and demonstrated my ability to learn, adapt, and grow in new positions.