Marie Curie ITN cQOM
Summary of the Scientific Achievements

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Description of research work / Goals achieved and progress towards them

Coupling several optomechanical systems to form arrays opens up new possibilities of exploring multimode systems and quantum-many-body dynamics. Promising candidates for experimental realizations of large arrays are optomechanical crystals [*Eichenfield et al., Nature 2009*] - small arrays (of up to 7 optomechanical systems) have already been realized with optomechanical micro disks [*Zhang et al., PRL 2015*].

Our particular interest was to make predictions about synchronization of optomechanical systems in the quantum regime. Synchronization is a widely known phenomena that can be observed in nature (e.g. flashing of fireflies) and has been applied in technology (e.g. electrical power grids). Since optomechanical systems are approaching the quantum regime, we aimed for effects of quantum noise on synchronization.

Our first goal was a numerical simulation of the full quantum behaviour of two coupled optomechanical systems. The main computational challenge of this approach is to deal with the exponentially growing Hilbert space, which eventually prevented us from simulating even larger arrays. Using the method of quantum jump trajectories [*Mølmer et al., JOSA B 1993*] we succeeded in simulating two coupled optomechanical systems.

Although feasible, the computation time needed is still high. Thus we additionally applied semi-classical Langevin equations to explore a larger parameter space and compare results (wherever possible) to the full quantum simulation.

These approaches allowed us to successfully simulate and interpret the synchronization behaviour in the quantum regime. It has been known before that optomechanical systems in the absence of noise (either quantum or classical) features two types of synchronization, called 0-synchronization (in-phase synchronization) or π-synchronization (anti-phase synchronization), and a bistable regime where both types of synchronization are stable solutions [*Heinrich et al. PRL 2011*]. We showed that, in the quantum regime, noise- induced transitions between 0- and π-synchronization can occur. For this purpose, we identified a useful measure to distinguish between the two synchronization states, also giving insight into the ratio of time spent in either state. Furthermore, we found noise- induced bistability, i.e. we observed switching between two synchronization states where classically (in the absence of noise) only one stable solution exists. These results have been published as:

"*Noise-induced transitions in optomechanical synchronization*", Talitha Weiss, Andreas Kronwald and Florian Marquardt, **New Journal of Physics 18, 013043 (2016)**

As a follow-up to this project, we focused on the often raised question, whether optomechanical systems (in the context of synchronization) allow for quantum states of the phase (e.g. superposition states instead of bistability).

A necessary condition to observe any quantum physical behaviour of phases is that the phase dynamics is not overdamped: In an overdamped regime, any quantumness is destroyed by decoherence much faster than the typical timescale of the system's dynamics. So far, optomechanical synchronization has only been described in the overdamped regime [*Heinrich et al., PRL 2011*].

To tackle this problem also in an analytical way, we study a Van der Pol oscillator that synchronizes to an external drive. A Van der Pol oscillator is a paradigm example of a self-oscillating system. To a certain extent it can be used as an approximation to a self- oscillating optomechanical system [*Walter et al., PRL 2014*], but also to trapped ions [*Lee et al., PRL 2013*], which makes it's behaviour of even more generic interest. Classically the Van der Pol oscillator is an extremely well-studied system and it is known that it features more involved phase dynamics, including a regime of underdamped phase motion and even self-oscillations of the phase [*Pikovsky et al., IJBC 2000*]. Our goal is to investigate if and how this classical behaviour translates to the quantum Van der Pol oscillator and demonstrate that this allows to do quantum physics with phases. For this purpose, we have derived an effective quantum model that includes the underdamped phase dynamics and gives access to the harmonic oscillator behaviour of the phase. In combination with numerical simulations of the full quantum model we can show that underdamped phase dynamics can also be observed in the quantum regime. Although a small damping is not sufficient to guarantee a small decoherence rate, we can determine the additional dephasing rate to identify parameters where both rates become small.

Currently we are in the process of ***preparing a publication on this topic***.

<u>Training received</u>

In order to learn more about the broader field of optomechanics and the basic techniques that are applied in different research groups, I have attended 5 ITN cQOM workshops at other universities:

- "*Fundamental noise sources*" - Hannover (2013), "*Theory of cavity optomechanics*" - Erlangen (2013),
- "*Experimental toolbox for cavity optomechanics*" - Paris (2014), "*Finite Element Modeling*" - Lausanne (2014),
- "*Levitation in (quantum) physics*" - Vienna (2015),
- Two annual workshops in Diavolezza (2015 and 2016).

These workshops were also great opportunities to get to know the other fellows of the ITN cQOM. Depending on the specific program, I was able to contribute a poster or talk about my own research.

Furthermore, I participated in two industrial workshops about "Taking an idea to a product", which gave interesting insights into industrial research and patent law:

- Attocube (Münich, 2013)
- IBM (Zürich, 2015)

At my hosting institution I was able to attend soft skill seminars in the context of a mentoring program (e.g. about rhetoric, project management, etc.). Furthermore, my hosting research group carried out weekly seminars (a chair seminar where various topics of physics are presented and a journal club where recent literature on optomechanics is discussed). I actively participated in these, thus continuously improving both my presentation and English skills.

<u>Dissemination and Conferences attended</u>

In addition, I was able to attend several conferences where I could present my research either in form of a poster or even as an oral presentation at

- "*Frontiers of Nanomechanics*" in Trieste (2013),
- ***Gordon Research Seminar*** and ***Gordon Research Conference*** about *"Mechanical systems in the quantum regime"* in Ventura in 2014 and 2016,
- ***DPG Frühjahrstagung*** (annual meeting of the German physical society) for Atoms, Molecules, Quantumoptics, and Plasmas in Heidelberg (2015),
- ***APS March Meeting*** in Baltimore (2016).

Participating in these conferences was a great chance to also get in touch with researchers beyond the scope of the ITN cQOM network, exchange ideas and broaden my knowledge.

Outreach Activities

Finally, I am involved in the outreach activity of the ITN cQOM that aims to contribute our knowledge about cavity optomechanics to Wikipedia. My task was to organize the improvement of the already existing Wikipedia article "Cavity optomechanics". I set up a structure for our improved version and shared the actual work of writing the new article with a few fellows from the ITN cQOM. The final editing of all parts (adjusting to Wikipedia format and style, making the individual contributions consistent) was also carried out by me. Our improved version of this Wikipedia article has been uploaded and is publicly accessible.