Quantum metric and plasmonic Bose-Einstein condensate (experiment)

Quantum Dynamics group/Academy Prof. Päivi Törmä

This is an experimental project, closely related to the theory summer project offered by the QD group. Therefore the beginning of the description for both projects is the same.

Nanoscale Bose-Einstein Condensates and lasers

Nanoplasmonics deals with surface plasmon polaritons (SPPs) which are light bound on the surface of a metal. The special feature is that such light can be confined to smaller scales than the wavelength of light (which is in micrometers): it can be called “nanolight”. “Nanolight” has special properties such as extremely high field intensity. SPPs are already applied in biosensors, and the most important future applications are envisioned to be novel light sources, solar energy harvesting, and cancer therapy. Our group has been pioneering the use of plasmonics to create novel types of coherent light sources, such as nanoscale lasers and, very recently, Bose-Einstein condensates (BEC). Bose-Einstein condensation is a phenomenon predicted by Bose and Einstein more than hundred years ago, and observed in a few different systems ever since. Our BEC produces coherent light somewhat similar to laser light, and is one of the fastest BECs known (dynamics in the sub-picosecond range). Our result was published in the top physics journal Nature Physics, you can read more via the following link as well as from the news at Helsingin sanomat, and see a video at youtube:
https://www.nature.com/articles/s41567-018-0109-9
https://www.hs.fi/tiede/art-2000005645499.html
https://www.youtube.com/watch?v=okZmnB3Hhb4

The QD group has also done groundbreaking theory work on the effect of quantum geometry on superfluidity: we have shown that paired electrons can become a superfluid that flows even in flat energy bands where single electrons cannot move. The explanation for this phenomenon is given by quantum geometrical and topological characteristics of the system that guarantee suitable overlaps of the electron wavefunctions. See the news
We discovered that flat band superfluidity is intimately connected to so called quantum metric, which measures distances between quantum states. Quantum metric is related to the Berry curvature and topological phenomena, a rapidly expanding research topic in modern physics.

In the future, the QD group will combine these two major findings to explore topological and quantum geometric properties of nanoscale lasers and BECs. We want to find out, for instance, whether strong effective interactions between photons – which would enable ultrafast all-optical processing, can be realized by quantum geometry. Another important question is whether coherence properties of the laser/BEC light can be controlled by topology.

The goal of this summer project is to perform the first measurement of the quantum metric in our nanoparticle array systems. In this context, the quantum metric tells about how the polarization properties of different modes of the system change with momentum. The work consists of 1) fabricating the nanoparticle arrays with electron-beam lithography in a clean-room environment, 2) optical measurements of the dispersions of the arrays with frequency and polarization resolved transmission experiments, 3) data analysis to extract the quantum metric from the measurement results – this part will be done in collaboration with theorists (see the theory summer project). The project is important not only as the first step for studying the effects of quantum geometry for plasmonic lasing and BEC, but also because the quantum metric has not been measured for any optical system so far!

**What will you learn in the project**

In the fabrication work you will learn a set of state-of-the-art nanofabrication methods and how to work in a cleanroom environment. You will also learn how to plan an experiment and perform it with an advanced optical measurement setup. You will learn data analysis and how to collaborate with theorists in order to do it successfully. Your scientific communication and collaboration skills will develop since you will work as a member of an active group.

Through your work, you will learn concepts related to nanoparticle arrays, optics, topological physics and quantum geometry. Being a member of the QD group, you will also learn about nanoscale lasing and BEC, although they are not necessarily part of this work – you may continue working on those in the future, if you wish. This work constitutes a Bachelor of Science thesis or a special assignment. If you wish to do a Master’s thesis, the topic can be extended to include studies of lasing and/or BEC.
Who supervises you and how

You will be supervised by P. Törmä and her group members. The group leader P. Törmä is one of the highly regarded scientists in the world in the fields of ultra-cold gases and nanoplasmonics. The group publishes in the topmost scientific journals such as Science, Nature Physics, Nature Communications, Physical Review Letters and Nano Letters. In the autumn 2013, P. Törmä obtained the prestigious ERC Advanced Grant, and in 2017 the Academy Professorship reflecting that the group and the research topics are evaluated as being at the very top level. By working in the group, you get a direct access to the frontline of research, and your work will get visibility.

The group members supervising this project are Dr. Akbar Syed and Ph.D. students Alessandro Cotrufo and Rebecca Heilmann.

You will meet the group leader at least once per week, and the second supervisor (Akbar, Alessandro, Rebecca) almost daily. We have a system of writing your special assignment/B.Sc thesis/M.Sc. piecewise during the summer, so that you will be able to complete it promptly after the summer.

More information about the group and the research:

You can also ask for more information from paivi.torma@aalto.fi

Interested in your future? See from the Alumni at the end of the page
where people who worked in our group have ended up, both in academia and industry.
Quantum metric and plasmonic Bose-Einstein condensate (theory)

Quantum Dynamics group/Academy Prof. Päivi Törmä

This is a theory project, closely related to the experimental summer project offered by the QD group. Therefore the beginning of the description for both projects is the same.

Nanoscale Bose-Einstein Condensates and lasers

Nanoplasmonics deals with surface plasmon polaritons (SPPs) which are light bound on the surface of a metal. The special feature is that such light can be confined to smaller scales than the wavelength of light (which is in micrometers): it can be called “nanolight”. “Nanolight” has special properties such as extremely high field intensity. SPPs are already applied in biosensors, and the most important future applications are envisioned to be novel light sources, solar energy harvesting, and cancer therapy. Our group has been pioneering the use of plasmonics to create novel types of coherent light sources, such as nanoscale lasers and, very recently, Bose-Einstein condensates (BEC). Bose-Einstein condensation is a phenomenon predicted by Bose and Einstein more than hundred years ago, and observed in a few different systems ever since. Our BEC produces coherent light somewhat similar to laser light, and is one of the fastest BECs known (dynamics in the sub-picosecond range). Our result was published in the top physics journal Nature Physics, you can read more via the following link as well as from the news at Helsingin sanomat, and see a video at youtube:

https://www.nature.com/articles/s41567-018-0109-9
https://www.hs.fi/tiede/art-2000005645499.html
https://www.youtube.com/watch?v=okZmnB3Hhb4

The QD group has also done groundbreaking theory work on the effect of quantum geometry on superfluidity: we have shown that paired electrons can become a superfluid that flows even in flat energy bands where single electrons cannot move. The explanation for this phenomenon is given by quantum geometrical and topological characteristics of the system that guarantee suitable overlaps of the electron wavefunctions. See the news

and further publications on the topic from our web-page
such as http://journals.aps.org/prl/abstract/10.1103/PhysRevLett.117.045303
and https://journals.aps.org/prb/abstract/10.1103/PhysRevB.98.220511
We discovered that flat band superfluidity is intimately connected to so called quantum metric, which measures distances between quantum states. Quantum metric is related to the Berry curvature and topological phenomena, a rapidly expanding research topic in modern physics.

In the future, the QD group will combine these two major findings to explore topological and quantum geometric properties of nanoscale lasers and BECs. We want to find out, for instance, whether strong effective interactions between photons – which would enable ultrafast all-optical processing, can be realized by quantum geometry. Another important question is whether coherence properties of the laser/BEC light can be controlled by topology.

The goal of this summer project is to provide theory support for the first measurement of the quantum metric in our nanoparticle array systems, and to find out lattice and nanoparticle configuration that show non-trivial geometrical and topological properties. In the context of nanoparticle arrays, the quantum metric tells about how the polarization properties of different modes of the system change with momentum. The work consists of 1) helping the experimentalists with data analysis to extract the quantum metric from measurements (this involves defining derivatives from a set of discrete data), see the experimental summer project, 2) finding out system configurations (nanoparticle shapes, lattice geometries) which show especially interesting quantum geometrical properties, such as finite quantum metric and/or Berry curvature. You will use both analytical calculations based on simplified models, as well as a numerical approach using a T-matrix method developed in the QD group. For more information about the T-matrix method see our recent article published in Physical Review Letters https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.122.013901 which is also a nice example of how theory and experiment intertwine in the QD group.

The project is important not only as the first step for studying the effects of quantum geometry for plasmonic lasing and BEC, but also because the quantum metric has not been measured for any optical system so far!

What will you learn in the project

You will learn the physics of nanoparticle arrays and basic theoretical concepts of quantum geometry and topology. You will master an advanced numerical method that is able to describe the modes of a rather complex optical system. Part of your work is in close collaboration with experimentalists and involves advanced data analysis. Your scientific communication and collaboration skills will develop since you will work as a member of an active group.
Through your work, you will learn concepts related to nanoparticle arrays, optics, topological physics and quantum geometry. Being a member of the QD group, you will also learn about nanoscale lasing and BEC, although they are not necessarily part of this work – you may continue working on those in the future, if you wish. This work constitutes a Bachelor of Science thesis or a special assignment. If you wish to do a Master’s thesis, the topic can be extended to include studies of lasing and/or BEC.

Picture on right: group theoretical analysis of the nanoparticle array modes, from https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.122.013901

Who supervises you and how

You will be supervised by P. Törmä and her group members. The group leader P. Törmä is one of the highly regarded scientists in the world in the fields of ultra-cold gases and nanoplasmonics. The group publishes in the topmost scientific journals such as Science, Nature Physics, Nature Communications, Physical Review Letters and Nano Letters. In the autumn 2013, P. Törmä obtained the prestigious ERC Advanced Grant, and in 2017 the Academy Professorship reflecting that the group and the research topics are evaluated as being at the very top level. By working in the group, you get a direct access to the frontline of research, and your work will get visibility.

The group members supervising this project are Senior University Lecturer Jani-Petri Martikainen and Ph.D. student Marek Necada. You will meet the group leader at least once per week, and the second supervisor (Jani-Petri, Marek) almost daily. We have a system of writing your special assignment/B.Sc thesis/M.Sc. piecewise during the summer, so that you will be able to complete it promptly after the summer.

More information about the group and the research: https://www.aalto.fi/department-of-applied-physics/quantum-dynamics-qd
You can also ask for more information from paivi.torma@aalto.fi

Interested in your future? See from the Alumni at the end of the page https://www.aalto.fi/department-of-applied-physics/quantum-dynamics-qd where people who worked in our group have ended up, both in academia and industry.