



PhD - Quantum Project

Research topics – Cycle 34

	Research topic	Acronym	Scientific References	PhD Programme
A	Production and certification of cheap QRNG based on intra-particle entanglement and applications to QKD	Q-Random	Pavesi (Physics), Mazzucchi (MAT)	Physics
B	Coupling of SiV centers in diamond to silicon-nitride cavities and waveguides	D-on-Si	Pucker (FBK - CMM), Chiappini (CNR-IFN)	Physics
C	Quantum topological photonics	QUANTOPHOT	Carusotto (CNR-INO), Pavesi (Physics), Bettotti (Physics)	Physics
D	Quantum simulator for open quantum systems	QOQS	Faccioli (Physics), Garberoglio (FBK - ECT*), Giorgini (Physics), Recati (CNR-INO)	Physics
E	Acceleration of nuclear physics calculations by quantum simulators	ANuPC-QS	Pederiva (Physics), Carusotto (CNR-INO), Dubois (LLNL Livermore), Quaglioni (LLNL Livermore)	Physics
F	Quantum droplets of ultra-cold atoms	Q-DROP	Recati (CNR-INO), Stringari (Physics), Wambach (FBK - ECT*)	Physics
G	Superconducting circuits for the Casimir effect	SOCCER	Casse (FBK - CMM), Falferi (CNR-IFN), Carusotto (CNR-INO)	Physics
H	Cold atom manipulation on silicon chips	CAMSiC	Ferrari G. (CNR-INO), Ghulinyan (FBK - CMM)	Physics



I	Design of practical multi-hop Quantum Key Distribution networks: trading risk, security and costs	MultiHop	Siracusa (FBK CREATE-NET), Massacci (ICT)	ICT
J	Definition and simulation of algorithms on an adiabatic quantum computer	AdiabaticQC	Serafini (FBC ICT), Passerini (ICT), Moretti (MAT)	ICT
K	Quantum tribology and related engineering applications, such as sensors, devices, motors and NEMS.	QTribology	Pugno (DICAM), Carusotto (CNR-INO), Taioli (FBK - ECT*)	ICAM
L	Monolithic Quantum Random Number Generator	SET-FREE	Massari (FBK), Pancheri (MMSE), Tomasi (FBK)	MMSE

Legend:

CNR: (Italian) National Research Council

FBK: Fondazione Bruno Kessler (Trento, Italy)

ICT: Information and Communication Technology

ICAM: Civil, Environmental and Mechanical Engineering

MAT: Mathematics

MMSE: Materials, Mechatronics and Systems Engineering

Topic A

Topic: Production and certification of cheap QRNG based on intra-particle entanglement and applications to QKD - Q-Random

P.I.: Lorenzo Pavesi (Dept. of Physics), Sonia Mazzucchi (Dept. of Mathematics)

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Synthetic description of the activity and expected research outcome

The main objective of the thesis is the development of a fully on chip self-testing quantum random number generator (QRNG) and of a quantum key distribution (QKD) optical link. Both themes are based on the innovative concept of intra-particle entanglement.

- J. C. Garrison, R. Y. Chiao, *Quantum Optics*, Oxford University Press, New York (2008).
 - Zahra Bisadi, Giorgio Fontana, Enrico Moser, Georg Pucker, and Lorenzo Pavesi “Robust Quantum Random Number Generation with Silicon Nanocrystals Light Source”, IEEE/OSA Journal of Lightwave Technology 35, 1588 - 1594 (1 May 2017).
 - A. Acin, L. Masanes, “Certified randomness in quantum physics” Nature 540 (2016), 213-219.
- BR Gadway, EJ Galvez, FD Zela, “Bell-inequality violations with single photons entangled in



momentum and polarization" J. Phys. B: At. Mol. Opt. Phys. 42 (2009) 015503

Ideal candidate (skills and competencies):

The PhD student enrolled in this project is assumed to be mainly an experimental physicist working at the Department of Physics, but he/she should be also able to collaborate with theorists of the field of classical and quantum probability and quantum information based at the Department of Mathematics.

Topic B

Topic: Coupling of SiV⁻ centers in diamond to silicon-nitride cavities and waveguides - D-on-Si

P.I.: Georg Pucker (FBK-CMM), Andrea Chiappini (CNR-IFN)

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Synthetic description of the activity and expected research outcome

Aim of the proposal is the development of a hybrid silicon nitride/diamond platform, with the potential for the development of optically or electrically triggered sources of bright single-photon emitters. The negatively charged silicon vacancy (SiV⁻) in diamond is an interesting candidate for realization of such a light source as it fulfils some of the required key criteria such as brightness, lifetime limited optical linewidths and a narrow inhomogeneous distribution of optical transition frequencies. The SiV⁻ is a spin ½ system with ground and excited states localized in the diamond band gap with the ZPL energy of 1.68 eV (737 nm) and up to 70% of the emission at RT can go to the ZPL. In many applications of SPEs, it is beneficial to integrate SPEs on chip within a photonic integrated circuit (PIC) especially to guarantee scalability of the technology.

The principle objectives of the research will be:

Optimization of the CVD diamond material properties to reduce strain effects (e.g. by optimisation of the growth conditions and by removal of strained interfaces by wet-chemical etching of outer layers and grain boundaries), and to optimise the transparency of the matrix;

Optimization and study of the SiV⁻ centers obtained by ion implantation or focused ion beam implantation and controlled thermal annealing, and fabrication of nanostructures (wires and pillars containing SiV⁻ centers);

Optical simulation and design of the coupled diamond silicon nitride systems and device fabrication;

Optical characterization of the hybrid diamond silicon nitride platform, which will include the characterisation of all the optical components, measurement of enhancement of photoluminescence and decay characteristics from SiV⁻ centers coupled to nitride cavities (at RT and cryogenic temperatures) and reduction of the numbers of SiV⁻ centers coupled to the optical cavities.



Ideal candidate (skills and competencies):

- The ideal candidate has competencies in at least one of the topics described below,
- Background in optical spectroscopy of vacancies in diamond or similar materials,
- Experience in optical spectroscopy of single emitting centers,
- Good background in quantum optics,
- Experience in material characterization with Raman-spectroscopy, AFM and related techniques,
- Basic experience in microfabrication;

Topic C

Topic: Quantum topological photonics - QUANTOPHOT

P.I.: Iacopo Carusotto (CNR-INO-BEC), Lorenzo Pavesi (Dept. of Physics), Paolo Bettotti (Dept. of Physics)

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Synthetic description of the activity and expected research outcome

The objective of this project is to investigate how silicon photonics devices can be used to study novel light propagation phenomena that extend to the optical context the quantum Hall effects of condensed matter physics. Topological effects will be used to protect light propagation from disorder as well as to obtain new forms of laser operation, with long-term perspectives into integrated quantum photonics applications.

The mostly theoretical activity will be carried out under the direct supervision of INO-CNR BEC Center staff in close collaboration with experimental colleagues for the phenomenological aspects, with the concrete possibility that successful predictions be immediately implemented in the UniTN labs.

Ideal candidate (skills and competencies):

- He/she should have a solid knowledge of electromagnetism and general optics and a master-level competence in the general concepts of quantum optics, solid-state physics, many-body physics and photonics. While a general familiarity with experimental techniques in these fields and with fabrication and material science aspects of photonics is welcome, a good capacity to work in team with experimentalists is essential. A general familiarity with advanced differential geometry and topology concepts is also welcome.
- He/she should have at least a basic expertise in numerical simulations and a proven ability to communicate in scientific english (written and oral)

Topic D

Topic: Quantum simulator for open quantum systems - QOQS

P.I.: Pietro Faccioli, Stefano Giorgini (Dept. of Physics), Alessio Recati (CNR), Giovanni Garberoglio (FBK - ECT*)



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Synthetic description of the activity and expected research outcome

The project aims at understanding the static and dynamic properties of an impurity immersed in a quantum bath. To this end, we will assess the performance of various theoretical models by comparing their results to experimental data on cold-atom systems acquired in a partner laboratory.

Many different physical regimes will be considered, such as a classical probe in a quantum environment or a quantum impurity in a bosonic or fermionic bath, covering different strengths of the impurity-environment interaction. Since only a few of the proposed models are amenable to analytic solutions, we expect to resort significantly to numerical calculations.

The principal outcome of this research will be the publication of our findings on international high-impact and peer-reviewed journals. A proposal for an international conference dealing with the topics of this research will be submitted to ECT* in 2020.

Ideal candidate (skills and competencies):

- Knowledge:
 - Required: basic knowledge on at least 2 of the following fields: Quantum Statistical Mechanics and Path-integral formalism, Cold-atom physics (Bose–Einstein condensates), Quantum Field Theory
 - Desired: Basic knowledge of the Theory of Open Quantum Systems
- Specific computer skills:
 - Required: experience in programming with at least one high-performance scientific language (C, C++, FORTRAN).
 - Preferred: working knowledge of numerical linear-algebra packages (BLAS, LAPACK) and the principal scientific libraries (GSL, FFTW)
 - Desired: experience with multithreaded or massively parallel programming (MPI)

Topic E

Topic: **Acceleration of nuclear physics calculations by quantum simulators - ANuPC-QS**

P.I.: **Francesco Pederiva (Dept. of Physics), Iacopo Carusotto (CNR)**

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Synthetic description of the activity and expected research outcome

One of the major tasks in modern nuclear physics is related to understanding the intimate relationship between the fundamental symmetries governing the standard model, and described by Quantum Chromo-Dynamics (QCD) and the forces arising between effective degrees of freedom, like baryons or mesons, characterizing the Universe at low temperature and densities typical of atomic nuclei. All nucleon-nucleon interactions contain a dependence on the relative spin/isospin state of the nucleons, dependence as clearly indicated by scattering experiments. One of the consequences of this dependence is the need of describing a system of A nucleons by means of wavefunctions containing a number of components scaling exponentially with A . This



fact strongly hinders the possibility of using *ab-initio* descriptions of the nuclear structure and dynamics beyond some relatively small nuclei. The aim of this project is to develop the software environment for existing quantum hardware based on the general circuit QED concepts (and in particular a new machine that is under development at Lawrence Livermore National Laboratory), with the aim of testing a possible quantum supremacy in the treatment of the expensive spin/isospin dependent parts of the nuclear Hamiltonian appearing in both real- and imaginary-time propagators used to calculate solutions for the many body problem.

Ideal candidate (skills and competencies):

The ideal candidate possesses a sound background in advanced quantum mechanics, and possibly good notions of group theory and geometry. A bit of knowledge of nuclear physics might help but is not strictly necessary, since the project is mostly concerned with the development of quantum algorithms and control theory.

Topic F

Topic: Quantum droplets of ultra-cold atoms - Q-DROP

P.I.: **Sandro Stringari (Dept. of Physics), Alessio Recati (CNR-INO BEC Center), Jochen Wambach (FBK-ECT*)**

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Synthetic description of the activity and expected research outcome

The recent experimental realization of **quantum droplets** of ultra-cold atoms has revealed the existence of a novel state of matter characterized by an ultra-dilute liquid phase where the stability is provided by quantum fluctuations.

The purpose of the project is the theoretical study of the equilibrium and out of equilibrium properties of these new quantum systems, developing both analytical and numerical techniques in the framework of quantum many-body theories.

The project is based on the complementary expertise of the scientific advisors in the fields of research of ultra-cold atomic gases, helium clusters and nuclei.

The PhD student will profit from the highly interdisciplinary environment provided by the Bose-Einstein Condensation Center (<http://bec.science.unitn.it/>) and the European Center for Theoretical Studies in Nuclear Physics and Related Areas (<http://www.ectstar.eu>) settled in Trento as well as by collaborations with the most prestigious experimental cold gas laboratories in the world.

Ideal candidate (skills and competencies):

- Knowledge of quantum many-body theories
- Motivation towards both analytical and numerical approaches



Topic G

Topic: **Superconducting circuits for the Casimir effect - SOCCER**

P.I.: **Gianluigi Casse (FBK), Paolo Falferi (IFN-CNR), Iacopo Carusotto (INO-CNR BEC Center)**

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Synthetic description of the activity and expected research outcome

The main objectives of the research activity are the fabrication and test of coplanar superconducting waveguides and/or resonators terminated by a SQUID acting as a tunable mirror, and to use them in quantum optics experiments to observe the Dynamical Casimir Effect and related zero-point quantum fluctuation effects in the microwave spectral domain.

The project will be carried out in a continuous regular interaction between three teams: theoretical team (INO-CNR BEC Center), fabrication team (FBK with photolithography and, in near future, e-beam lithography), and testing team (IFN-CNR with 20 mK dilution refrigerator).

The PhD student will be given the opportunity to participate in all the activity, theoretical and experimental, with the support of the three teams. During the PhD, she/he will be trained on the physics of devices such as SQUIDs, Josephson junctions and microwave resonators that are the building blocks of circuit-QED, one of the most promising approaches to quantum technologies.

Ideal candidate (skills and competencies):

- She/he should have a solid knowledge of electromagnetism and a master-level competence in the general concepts of solid-state physics. She/he should be keen on learning experimental techniques in the following fields: low temperature physics, superconducting microwave technologies, microfabrication technologies and material science. She/he should have a good capacity to work in team with experimentalists combined with a good understanding of theoretical concepts and a manifest ability to work in team with theorists.
- She/he should have a proven ability to communicate in scientific english (written and oral)

Topic H

Topic: **Cold atom manipulation on silicon chips - CAMSiC**

P.I.: **Gabriele Ferrari (CNR-INO), Mher Ghulinyan (FBK-CMM)**

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Synthetic description of the activity and expected research outcome

The project aims at a new paradigm for the integration of cold atoms quantum sensors on silicon chips through the demonstration of key atomic manipulation elements integrated in silicon-based devices. During the thesis, the PhD student will assimilate key technologies, concepts and methods from both partners at the BEC Center (<http://bec.science.unitn.it>) and FBK (<http://www.fbk.eu>). He/she will be called to find the synthesis to devise novel protocols and



designs employing numerical simulative approaches and acquiring competence in the domain of cold atom manipulation, silicon microfabrication and silicon photonics.

Ideal candidate (skills and competencies):

- the ideal candidate should possess good knowledge of optics, materials science, quantum mechanics. Knowledge in basic programming with Matlab or Mathematica is welcome, but not essential.

Topic I

Topic: Design of practical multi-hop Quantum Key Distribution networks: trading risk, security and costs - MultiHop

P.I.: **Domenico Siracusa (FBK-CREATE-NET), Fabio Massacci (ICT)**

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Synthetic description of the activity and expected research outcome

Quantum Key Distribution (QKD) enables independent parties to exchange secret random bit sequences (keys) with an arbitrary upper bound on the information leaked to potential eavesdroppers.

The main objective of this thesis is to study the trade-off between cost, coverage, robustness and throughput of QKD overlays on large optical transport networks. The security of large overlays using relay nodes to extend QKD's range will also be addressed, e.g. via network coding techniques.

The metrics developed to evaluate these trade-offs will be incorporated into optimal, approximated and heuristic design techniques for future QKD networks, which will be designed, developed and tested as part of the thesis.

Ideal candidate (skills and competencies):

- Knowledge of mathematical programming (linear, mixed integer linear) and approximation algorithms, as well as more traditional programming paradigms
- Knowledge of network security protocols and models
- Knowledge of network design algorithms is preferred
- Knowledge of quantum communications, and specifically key distribution is preferred
- Familiarity with Linux-based environments is preferred

Topic J

Topic: Definition and simulation of algorithms on an adiabatic quantum computer - AdiabaticQC

P.I.: **Luciano Serafini (FBK), Andrea Passerini (ICT), Valter Moretti (MAT)**



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Synthetic description of the activity and expected research outcome

The research activity will be focused on developing and testing a methodology for encoding algorithms in the target Hamiltonian and in the evolution scheme of an Adiabatic Quantum Computer. In particular main goals are: The direct implementation and simulation of the Grover algorithm on the target adiabatic architectures, the implementation of a compiler based on the universality theorem of adiabatic computing to generate the Hamiltonian that encodes the considered problem. The strategy will be modeling the adiabatic scheme (problem Hamiltonian and a suitable evolution) as a varying scalar function and learning it with Bayesian Optimization and reinforcement learning. A final research outcome will be the application of the methodology to implement, simulate and test a version of the genetic quantum algorithm.

Ideal candidate (skills and competences):

- Either master's degree in Physics or master's degree in Computer Science;
- Bases of either quantum computing or machine learning;
- Attitude to interdisciplinary research;
- Attitude to learn new subjects;
- Knowledge of one major programming language;

Topic K

Topic: Quantum tribology and related engineering applications, such as sensors, devices, motors and NEMS - QTribology

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Synthetic description of the activity and expected research outcome

Quantum effects in sliding friction have not been discussed in depth in the tribology community. In most cases, in fact, the forced motion of atoms, molecules, and solids is considerate and simulated only with classical approaches [1]. It was not until recently that the idea of “quantum friction” has gained considerable interest among the scientific community. In order to understand quantum friction properties, a large number of studies have been carried out to model surface-surface (Casimir) and particle-surface (Casimir-Polder) properties [2]. The study of Casimir effect, which arise from the quantum vacuum fluctuations of the electromagnetic field [3], allowed to identify the existence of a tangential component of the force when sliding between two plates occurs [4]. The tangential component and its ratio with the normal one, lead to what we could define as quantum friction coefficient. The aim of the project is thus, to study the effect of different plates geometries on the tangential and longitudinal components of Casimir force between the plates as a function of the detailed shape of the plates, their dielectric and magnetic properties, as well as their relative velocity [4, 5]. In order to analyse the macroscopic frictional properties of the material a multiscale approach will be developed taking into account complex topologies and even hierarchical surfaces. To achieve the aforementioned goal both static and dynamic Casimir forces will be considered, so to take into account both conservative and dissipative processes. It will be necessary to develop an appropriate numerical code, also to take into account the roughness and



the geometries of surfaces using a multiscale approach, in order to understand how the size and shape of the texturing of the plates influence the friction properties of the system. Furthermore, the study will also focus on hierarchical surfaces, already considered in macroscopic systems [6]. In particular, the Casimir effect -first predicted as a coupling between neutral metals due to electromagnetic fluctuations- represents a force of quantum origin between objects of macroscopic dimensions. The same type of force arises between atom-surface configurations (Casimir-Polder effect); however, the realization of such interaction is more general, in particular the Casimir type of force is encompassed in the broader definition of “dispersion forces”, showing a common origin of the Casimir and Van der Waals (vdW) interactions. Both are indeed due to dipole fluctuations, with the electromagnetic energy of dipoles stored in their fluctuating electromagnetic fields. While the Casimir force is experimentally relevant at micron/submicron separations, this force is ubiquitously present between any types of objects, having far reaching consequences in our understanding of materials stability as well as in the operation of devices at the microscales and nanoscales. In this project we aim at studying from first-principles methods the effect that Casimir and vdW interactions may play in the stability and in shaping the configurations of several materials and how this phenomenon, which is inherently long ranged, depends upon the electromagnetic boundary conditions and response properties of the materials. To do so a number of observables of real materials must be assessed, most notably the electron correlation energy, as via the adiabatic connection fluctuationdissipation theorem (ACFDT) the latter is directly correlated to the vdW and Casimir forces. Computational methods beyond DFT or vdW-corrected DFT, will be used for calculating vdW interactions with sufficient accuracy. In particular the many-body correlation energy will be assessed at different level of theory, from mean-field approaches to many-body perturbation theory and Quantum Monte Carlo, in order to treat accurately the electron degrees of freedom of the atomistic systems. Furthermore, by using ab-initio simulations we will put forward a broader materials perspective of vdW and Casimir interactions, to study the importance of dispersive forces in several novel materials, including graphene, 2D dichalcogenides, 2D oxides or other honeycomb layers, such as silicene, germanene, or stanene, or heterostructures built by stacking different types of layers, where vdWs play a pivotal role. Especially using as test cases novel lowdimensional materials, such as graphene, composites, and biosystems, and other materials with Dirac spectra, such as topological insulators, Chern insulators, and Weyl semimetals, we will investigate the possibility to engineering the Casimir or vdW field, as the surface of such materials has a distinct nature from the bulk. Indeed, we devise that the Casimir and vdW interactions can be strongly affected by the following two features: non-trivial shapes of these structures, characterised by a reduced dimensionality, and Dirac-like behaviour of fermions within the material together will induce novel behaviors of these interactions. Of course for an accurate description of long-ranged vdW and Casimir interactions in these Dirac-like structured materials, novel first-principles methods for treating the Coulomb interactions must be used and possibly developed. Indeed, the assessment of many-body effects in the calculation of the vdW and Casimir energy is crucial for an accurate modeling of realistic materials; this issue is still debated in condensed matter and materials science. Nevertheless, the inclusion of these effects in first-principles simulations is critical for evaluating the performances of a wide range of materials in technological applications, including finite and periodic molecular systems, insulating and semiconducting solids, and interfaces between organic and inorganic systems. Furthermore, non trivial structures such as those mentioned above can be used not only as a platform where magnitude and sign of the Casimir forces vdW can be tailored, but they might represent a novel paradigm for bridging concepts from condensed-matter, high energy, and computational physics. Finally, the importance of the vdW interaction extends to organic and biological matter. We plan to investigate from ab-initio simulation even the effect that Casimir and vdW may have in the development of properties in these biosystems. An interesting application of these results is the possibility to realize Quantum Sensors, Devices and Motors, also filling the gap between Molecular Motors and Nano Electro Mechanical Systems (NEMS). Plates in NEMS and MEMS



could also be experimentally realized using different techniques. The plate surface topology can influence the contribution of the Casimir energy and related generated force and thus working principle of the device, targeting the realization of a proof of concept.

Deliverables: presentation of the research results at international conferences and workshop on Quantum Physics and tribology, publication of the research results in international peer-reviewed journals.

Ideal candidate (skills and competencies):

- Knowledge of physics and/or engineering
- Specific skills in theory and/or simulations & programming

Topic L

Topic: **Monolithic Quantum Random Number Generator**

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Synthetic description of the activity and expected research outcome

Random Number Generators (RNG) are essential building blocks for establishing a secure communication. Nowadays the advent of emerging technology, such as Internet of Things, enhances the need to ensure the challenging task to build a secure communication among all devices belonging to the network.

The objective of the present PhD project is the study and the design of a small and cheap Quantum RNG (QRNG) to be embedded in tiny devices. For this reason, the idea of the project is to focus the design on a monolithic solution preferably made in standard CMOS technology.

The activity will be divided in three main parts: 1. Study and design of the device, being the core of the QRNG, through experimental observations and simulations; 2. Design of a front-end electronics that allows properly biasing and processing the incoming data; 3. Analysis of the output sequence through common tools or using custom processing to remove possible non-idealities.

The project will envisage the design and characterization of an ASIC as final demonstrator of the activity.

A.Tomasi et al. "Model, validation, and characterization of a robust Quantum Random Number Generator based on photon arrival time comparison" IEEE Journal of Lightwave Technology, June 2018

Ideal candidate (skills and competencies):

- Knowledge of semiconductor physics;
- Basic knowledge of analog and digital circuit design
- Laboratory experience
- Programming experience