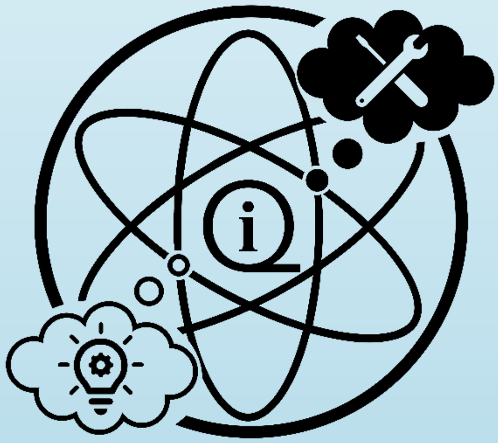
VCQ & AppQInfo Summer School 2022

Concepts & Applications of Quantum Information

Vienna, 29.08. – 02.09.2022
Find the schedule at vcq.quantum.at



Information Booklet

Contents

Information

Important Information

Welcome to the VCQ and AppQInfo 2022 Summer School on Concepts and Applications of Quantum Information! This leaflet contains important administrative information, which we hope will be of help during the event.

Location

This event takes place at the Faculty of Physics of the University of Vienna (main entrance: Strudlhofgasse 4, 1090 Vienna).

Lecture hall

The lectures will take place in the Christian-Doppler lecture hall on the 3rd floor. Coffee will be available in front of the lecture hall during coffee breaks.

Registration

The registration opens on Monday 29th August 2022 in front of the Christian-Doppler lecture hall at 8:30h. You will also be able to enlist for the guided lab tours on Monday.

Timetable and abstracts

You can find the timetable and the information about student talks, poster contributions and speakers online on our website.

COVID

You will be required to wear an FFP2 mask during lectures. You can find the current Austrian and Viennese COVID regulations here. The regulations for the University of Vienna can be accessed in German or in English.

Poster session

The poster sessions will be held on Tuesday 30th August and Thursday 1st September from 16:30h to 18:00h in the Ernst Mach lecture hall, 2nd floor. Participants that will present a poster should mention this at the registration desk, where they will receive further instructions.

Lab tours

There are planned lab tours on Friday 2nd September from 14:00h to 16:30h. Please write your name in the registration lists available at the reception desk upon arrival.

Lunch breaks

For available lunch options near the Faculty of Physics, you will find some suggestions included in the welcome pack.

Viennese welcome

We invite you to drinks and snacks at the Vienna City Beach Club on Monday evening from 18:30. We will depart together after the last lecture on Monday with public transport or you can make your own way there. You can find more information about the venue here.

Swimming is possible, so don't forget to bring a towel and swimwear!

Conference dinner

The conference dinner will take place on Wednesday 31st August at 18:00h at the Stiegl Ambulanz. We will walk there together after the last lecture or you can make your own way there. You can find more information about the venue here.

Important Information

Internet

Internet connection at the University of Vienna is available via eduroam.

Code of conduct

The organisers see diversity as an asset. We are committed to making this summer school productive and enjoyable for everyone involved, regardless of their specific characteristics. You can find our house rules here and the code of conduct here. If you feel the principles stated in these documents have not been followed by any attendee of the summer school, please speak, in confidence, to one of the points of contact:

Ksenija Simonović, University of Vienna +43 664 383 1808 ksenija.simonovic@univie.ac.at	Philipp Rieser, University of Vienna +43 680 204 6190 philipp.rieser@univie.ac.at

Sponsors

This summer school has been generously sponsored by the following partners:

Vienna Center for Quantum Science and Technology (VCQ)	Quantum Technology Laboratories GmbH (qtlabs)
Thorlabs GmbH	AppQInfo

Local organisers

Nadine Hilmar, VCQ	
Shreyas Gulhane, Vienna University of Technology	Ksenija Simonović, University of Vienna
Lennart Jehle, University of Vienna	Céline van Valkenhoef, University of Vienna
Philipp Rieser, University of Vienna	Zhenghao Yin, University of Vienna

Emergency contacts

In case of emergency, please feel free to contact:

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Finally

We are looking forward to five days of exciting talks, innovative posters and lively discussion. Enjoy the VCQ and AppQInfo 2022 Summer School on Concepts and Applications of Quantum Information!

Organized By

Vienna Center for Quantum Science and Technology (VCQ)

The VCQ is a joint initiative of the University of Vienna (Universität Wien), the Vienna University of Technology (TU Wien), the Austrian Academy of Sciences (ÖAW), and the Institute of Science and Technology Austria (ISTA), which unites quantum physicists of Vienna’s research institutions in one collaborative center.

The VCQ organizes a summer school every year where young PhD/Master/Bachelor students attend the lectures by the speakers around the fields of quantum sciences. This year, VCQ summer school is enhanced by the collaboration with AppQInfo in addition with company sponsors qtlabs and Thorlabs.

Applications and Hardware for Photonic Quantum Information Processing (AppQInfo)

Funded under the Marie Skłodowska-Curie Actions programme, the “AppQInfo” will train early-stage researchers in state-of-the-art integrated quantum photonics, one of five critical key enabling technologies for Europe. In this collaboration, young researchers will work on 15 interdisciplinary projects from Universities of Europe, Canada and Japan which will focus on developing feasible long-distance quantum communications from urban-scale networks to satellite-based systems.

It is our pleasure to welcome the AppQInfo international training network as co-organiser of this year’s summer school.

Company Sponsors

Thorlabs Crystalline Solutions, Santa Barbara, California USA

Of course all optics labs around the globe are aware of Thorlabs and their famous lab snacks. Being one of the giants in the optics industry, Thorlabs typically grows by acquiring startups to add additional technologies to their ever growing catalog and product portfolio. Crystalline Mirror Solutions (CMS) was once such a startup, originally founded by Dr. Garrett Cole and Prof. Dr. Markus Aspelmeyer of University of Vienna in 2012. In December 2019 CMS was acquired by Thorlabs Inc.

As a Marie Curie Fellow at the Austrian Academy of Sciences (ÖAW) and the University of Vienna, Garrett worked on novel quantum optomechanical systems. This work led to the development of crystalline coatings and the founding of CMS. In his talk he will provide an overview of the technology, as well as describe the launch of the startup. It will be exciting to learn about his path from research to entrepreneurship. On Tuesday the 30th Aug at 9:10 am, Garrett is going to discuss his exciting journey which would help others learn from his experience.

Quantum Technology Laboratories, Vienna, Austria

Quantum Technology Laboratories GmbH (qtlabs) provides solutions for secure quantum communication. The start-up was founded in 2017 in Vienna and moved to a bigger location at Wienerberg just last month to account for the ever-growing team of 17 employees, led by co-founders Dr. Thomas Scheidl and Dr. Rupert Ursin. With over 20 years of experience in the field of quantum science and technology, the qtlabs team is dedicated to developing and implementing quantum key distribution systems and optical communication technology. In particular, qtlabs works on satellite-based communication systems including both the space and the ground segment. Furthermore, applications in quantum sensing, quantum metrology, and related fields are being developed.

qtlabs with their focus on quantum applications and strong Viennese base is the perfect match for this event. We are happy to invite them and excited to know about their approach in this Second Quantum Revolution. On Wednesday the 31st Aug at 12:15 pm, qtlabs are going to present their amazing venture.

Speakers

Yelena Guryanova
IQOQI Wien, Austrian Academy of Sciences

Fundamentals of Quantum Information

About:
Yelena Guryanova completed her PhD in 2016 at the University of Bristol in the UK. Since then she worked for two years as a postdoc at the Institute for Quantum Optics and Quantum Information (IQOQI), Vienna, after which became group leader of the Young Independent Research Group, a joint group between the University of Vienna and IQOQI. Her research topics include quantum non-locality, thermodynamics and causality in the framework of higher-order operations.

Talk Abstract:
In these lectures, Yelena will introduce concepts of Quantum Information, which will form the basis on which subsequent lectures will build.

Xiao Xue
Qutech Institute, TU Delft

Quantum Computing

About:
Xiao Xue is a postdoc research fellow at QuTech, TU Delft. He accomplished his PhD dissertation in 2022, supervised by Prof. Lieven Vandersypen (director of QuTech), on quantum computing with spin qubits in silicon, covering the topics of high-fidelity quantum gates, quantum nondemolition measurement, cryogenic quantum control, etc. Now he is working on coupling remote spin qubits using microwave photons in a superconducting resonator. So far, he has published 6 first-authored papers, including 2 in Nature and 2 in Physical Review X. He published in total 10 journal articles and 4 conference proceedings, and he owns 1 US patent. In addition, he serves as a reviewer for Physical Review Letters, Nano Letters, etc.

Talk Abstract:
In this lecture, I will first describe the basics of quantum dots and spin qubits in a semiconductor. Then I will discuss the recent progress in experimental quantum information processing with spin qubits and the application of quantum dots in quantum simulations.

Tobias Heindel
Institute of solid state physics, TU Berlin

Quantum Communication

About:
Tobias Heindel received his PhD in physics from Julius-Maximilians-Universität Würzburg, Germany, in 2014 with the thesis title "Electrically pumped quantum-dot single-photon sources for quantum communication". After 2014 he worked as postdoctoral researcher at Technical University of Berlin pushing the performance of deterministically fabricated quantum light sources for applications in quantum information processing. Since 2018 Dr. Heindel leads the group Quantum Communication Systems at the Institute of Solid States Physics of Technical University of Berlin, which aims at the development of a quantum-secured communication testbed at the university campus. Dr. Tobias Heindel received the Karl-Scheel-Prize 2020, being the most significant award of the Physical Society in Berlin (PGzB). During his talk he will focus on practical QKD with solid state emitters and their impact for future networks.

Talk Abstract:
In recent years, tremendous progress has been achieved in the engineering of solid-state-based quantum light sources. In this context, semiconductor quantum dots (QDs) are among the most promising candidates for implementations of quantum information [1]. In my talk, I will review our progress in this field, ultimately striving towards quantum networks at global scales. I will discuss the development of novel building blocks, including fiber-pigtailed quantum devices [2,3] and plug&play benchtop single-photon quantum key distribution (QKD) systems [4], as well as spin-photon interfaces [5]. I show how to optimize and certify the performance of QKD systems [6] and report on our recent efforts in transferring our knowledge to advanced protocols and different technology platforms, including quantum emitters in 2D materials [7]. Assembling these building blocks to functional multi-partite quantum networks is a grand challenge in quantum technologies which will be tackled in my group.

[1] D. A. Vajner et al., Advanced Quantum Technologies 2100116, Invited Review Article (2022)
[2] L. Rickert et al., Optics Express 27, 36824 (2019)
[3] L. Rickert et al., Applied Physics Letters 119, 131104 (2021)
[4] T. Gao et al., Applied Physics Reviews 9, 011412 (2022)
[5] T. Heindel et al., APL Photonics 2, 121343 (2017)
[6] T. Kupko et al., npj Quantum Information 6, 29 (2020)
[7] T. Gao, M. von Helversen, C. Anton-Solanas, C. Schneider, and T. Heindel, Atomically-thin Single photon Sources for Quantum Communication, arXiv:2204.06427 (2022)

Gian Luca Giorgi
IFISC, University of the Balearic Islands

Quantum Reservoir Computing

About:
Gian Luca Giorgi has a University degree and a Ph.D. in Physics from "La Sapienza" University of Rome, Italy. His scientific interests include the areas of quantum information and computation, quantum complex systems, and artificial intelligence in the quantum domain. He is a member of IFISC (Institute for Cross-Disciplinary Physics and Complex Systems) as a "Beatriz Galindo" Distinguished Investigator.

Talk Abstract:

Reservoir Computing (RC) and extreme learning machines are machine-learning paradigms that make use of the information processing capability of complex dynamical systems [1]. Recently, quantum systems have been suggested as promising candidates for reservoir computing due to the significant growth in phase space degrees of freedom [2].

In this lecture, I will first introduce the general concepts and working principles of reservoir computing in the context of artificial neural networks, and then I will define the properties and minimal ingredients that physical systems need to satisfy to be employed as reservoir computers. Then, I will motivate the use of quantum systems for reservoir computing and describe the existing theoretical and experimental approaches [3].

Special attention will be devoted to the physics behind quantum reservoir computing, in particular regarding the phenomenon of dynamical phase transitions [4]. Another fundamental issue tackled in this lecture will be represented by the role of quantum measurements in RC, the limitations they introduce, and the possible way to overcome these limitations.

[1] H. Jaeger, The echo state approach to analysing and training recurrent neural networks-with an erratum note, German Natl. Res. Center Inf. Technol. GMD Tech. Rep. 148, 13 (2001); W. Maass, T. Natschläger, and H. Markram, Real-time computing without stable states: A new framework for neural computation based on perturbations, Neural Comput. 14, 2531 (2002).

[2] K Fujii and K Nakajima, Harnessing disordered-ensemble quantum dynamics for machine learning. Physical Review Applied, 8, 024030 (2017).

[3] P Mujal, R Martínez-Peña; J Nokkala; J García-Beni; GL Giorgi; MC Soriano, R Zambrini. Opportunities in Quantum Reservoir Computing and Extreme Learning Machines. Advanced Quantum Technologies. 4, 2100027 (2021).

[4] R Martínez-Peña, GL Giorgi, J Nokkala, MC Soriano, R Zambrini, Dynamical phase transitions in quantum reservoir computing, Physical Review Letters 127, 100502 (2021).

Ralf Schützhold
Helmholtz Zentrum, Dresden Rossendorf

Quantum Simulators

About:
Prof. Dr. Ralf Schützhold is the director of the Department of Theoretical Physics at the Helmholtz-Zentrum Dresden-Rossendorf, Germany and full professor for Theoretical Physics at the Technische Universität Dresden, Germany. After receiving his doctorate in 2001, he obtained a Feodor-Lynen fellowship from the Humboldt foundation and moved to the University of British Columbia in Vancouver, Canada in order to work with William G. Unruh, mainly on analogies between black holes and laboratory systems. With an Emmy-Noether fellowship from the German Research Foundation (DFG), he returned to Germany in 2003 and was appointed full professor for Theoretical Physics at the University of Duisburg-Essen, Germany in 2008. His research interests include the physics in strong fields and strongly correlated systems as well as quantum information technology.

Special emphasis is placed on analogies between different areas, such as fundamental effects (for example Hawking radiation) on the one hand and laboratory physics (e.g., ion traps, cold atoms, graphene etc.) on the other hand.

Talk Abstract:
After a general introduction into quantum simulators, this lecture will be devoted to simulations of fundamental phenomena. To this end, the underlying basic principles of various fundamental effects will be introduced briefly. Afterwards, several laboratory systems will be discussed which display analogous effects — in the spirit of the famous quote from Richard Feynman: “The same equations have the same solutions.”

Nathan Wiebe

Assistant Professor, Department of Computer Science, University of Toronto. Also affiliate physicist at Pacific Northwest National Laboratory

Quantum Information & Machine Learning

About:
Nathan Wiebe is a researcher in quantum computing who focuses on quantum methods for machine learning and simulation of physical systems. His work has provided the first quantum algorithms for deep learning, least squares fitting, quantum simulations using linear-combinations of unitaries, quantum Hamiltonian learning, near-optimal simulation of time-dependent physical systems, efficient Bayesian phase estimation and also has pioneered the use of particle filters for characterizing quantum devices as well as many other contributions ranging from the foundations of thermodynamics to adiabatic quantum computing and quantum chemistry simulation. He received his PhD in 2011 from the University of Calgary studying quantum computing before accepting a post-doctoral fellowship at the University of Waterloo.

Wiebe currently holds a Joint Appointment in the High-Performance Computing group at PNNL and is an assistant professor of Computer Science at the University of Toronto. Wiebe also holds an affiliate professorship in the Department of Physics at the University of Washington.

Talk Abstract:
In this talk I will review the topic of quantum simulation and show how these algorithms can be used in order to solve important problems in chemistry and quantum field theory. In particular, I will review simulation of chemistry using first and second quantization and show how algorithms such as Trotter-Suzuki algorithms and qubitization can be used to solve important simulation problems. Finally I will discuss how such ideas can be hybridized and algorithms that divide up the quantum simulation problem over different algorithms based on the features of the part of the molecule that we wish to simulate.

Ivette Fuentes
Institute of physics & astronomy, University of Southampton

Relativistic Quantum Information and Metrology

About:
Ivette Fuentes earned doctoral degree at Imperial College London in 2003 under the supervision of Peter Knight and Vlatko Vedral, moving on to become a postdoctoral fellow at the Perimeter Institute for Theoretical Physics. She is a professor in physics at the university of Southampton. She researches at the overlap of Quantum Theory and General Relativity, where she pioneered the study and application of quantum information and metrology in curved space time. Her current focus lies with the application of quantum technologies for fundamental physics proposing new ways to use quantum systems to measure gravitational waves, dark energy and dark matter.

Talk Abstract:
The insight that the world is fundamentally quantum mechanical inspired the development of quantum technologies including quantum computation, communications and metrology. However, the world is not only quantum but also relativistic, and indeed many implementations of quantum information tasks involve truly relativistic systems. In this lecture series I consider relativistic effects on entanglement in flat and curved spacetimes. I will emphasize the qualitative differences to a non-relativistic treatment, and demonstrate that a thorough understanding of quantum information theory requires taking relativity into account. The exploitation of such relativistic effects will likely play an increasing role in the future development of quantum technologies. The relevance of these results extends beyond pure quantum information theory, and applications to quantum metrology and to foundational questions in cosmology and black hole physics will be presented.

Students' Contributions

Student Talk Abstracts

VCQ 2022 Summer School [redacted]

Nicolás Medina Sánchez

University of Vienna

<u>Nicolás Medina Sánchez</u>[1], Borivoje Dakić[2]

[1] *University of Vienna*
[2] *Institute of Quantum Optics and Quantum Information (IQOQI)*

One of the main consequences of the indistinguishability of particles in quantum theory is the existence of only two types of particles, bosons and fermions. They are determined by the exchange symmetry of the corresponding multiparticle wave functions. The symmetrization postulate states that those wave functions are symmetric under exchange for bosons and antisymmetric for the fermionic case. However, the operational meaning of the exchange symmetry is not clear, given that exchanging particles among a specific type of modes is not generally well-defined.

One specific case is when modes are positions in physical space, then exchange symmetry can be simulated by adiabatic displacement of particles. It is known that in this scenario is possible to proof the symmetrization postulate when the displacements occur in configuration spaces of dimension greater or equal than 3 [1]. Unfortunately, the reasoning of that proof requires coupling quantum theory with the geometry of the configuration space, an object that is not quantum, even though we know that the existence of bosons and fermions is a purely quantum phenomenom that in principle should not require adding elements exterior to the theory.

In this work we study an approach to the symmetrization postulate from an operational point of view. Assuming only the validity of quantum theory and a sense of *locality* among modes we can almost reproduce the Fock space structure for quantum particles, getting two families of particles, bosonic-like and fermionic-like. These families curiously contain though new types of statistics consistent with quantum theory, apart from bosons and fermions. These new statistics can be used to treat problems in particle theory, cosmology and condensed matter physics that will be briefly discussed.

[1] J. M. Leinaas and J. Myrheim. On the theory of identical particles, Jan 1977.

VCQ 2022 Summer School [redacted] Few-Mode-Fiber technologies for Quantum Communication Applications

A. Alarcón[1], **J. Argillander**[1], **D. Spegel-Lexne**[1], **and G.B. Xavier**[1]

[1]*Institutionen för Systemteknik, Linköpings Universitet, SE-581 83 Linköping, Sweden*

Given the enormous growth of data traffic worldwide, security has become a fundamental pillar of communication systems [**1**]. Quantum communications emerge as a solution to encrypt data between two users where properties of nature are used as the basis for encryption operations. In order to carry out this task, a quantum communications system must have a suitable platform for the transport of single photons[**2**], and the encryption process must be performed from a reliable source of randomness [**3**].

Current photonic technologies have focused much of their efforts on moving towards highly secure systems with high bandwidth, which has stimulated the integration of current optical communication networks with emerging quantum communication systems [**2**]. Spatial division multiplexing (SDM) has made it possible to use the transverse spatial properties of a light beam to multiplex information and increase data transport capacity. We have taken advantage of these advances to encode single-photons in terms of their transverse spatial modes.

Due to the ability to simultaneously propagate more than one spatial mode through its core, few-mode-fibers (FMF) have great potential to become a key element in future optical and quantum communications infrastructures. Our FMF-based optical platform has demonstrated three important results so far: 1)it is possible to generate any set of bases in the two-dimensional Hilbert space by using the well-known linearly polarized (LP) spatial modes and their coherent superpositions to create photonic quantum states [**4**, **5**]. 2) we show that we can propagate those quantum states over 500 m of FMF [**4**]. 3) By slightly changing the configuration, we can also implement a quantum random number generator where the randomness originates from measurements of spatial modal quantum superpositions of the modes LP_{11a} and LP_{11b}.

Our platform is fully compatible with optical networking hardware by using standard components that operate in the 1550nm telecommunications window.

References

[1] G. B. Xavier and G. Lima, *Commun. Phys.* **3**, 9 (2020).

[2] A. Alarcón, *Licentiate dissertation, Linköping University Electronic Press.* (2022)

[3] M. Herrero-Collantes and J.C. Garcia-Escartin, *Rev. Mod. Phys.* **89**, 015004 (2017)

[4] A. Alarcón, J. Argillander, G. Lima and G. B. Xavier, *Phys. Rev. Appl.* **16**, 034018 (2021).

[5] A. Alarcón, J. Argillander, and G. B. Xavier, in *Applied Industrial Optics* (2021),

Entangling microwave with optical photons [redacted]

Rishabh Sahu[1], Liu Qiu[1], William Hease[1], Georg Arnold[1], Yuri Minoguchi[2], Peter Rabl[2], Johannes Fink[1]

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[2] *Vienna Center for Quantum Science and Technology, Atominstitut, TU Wien, 1040 Vienna, Austria*

Quantum entanglement lies at the heart of quantum physics enabling applications such as sensing, communication and computation to have a quantum advantage over their classical counterparts [1]. Future quantum networks would include remote quantum computational nodes with quantum memories and repeaters seamlessly communicating with each other via flying optical qubits [2]. Many of these quantum processing technologies work in the gigahertz domain in cryogenic environment [3, 4]. Connecting them remotely an optical network will require microwave-optical entanglement. However, so far such entangled states could not be prepared due to the incompatibility of low loss superconductivity and high energy optical photons that prevented the required ultra-low noise conditions. Here, we demonstrate the deterministic preparation of an entangled microwave-optical state in the continuous variable domain that is squeezed by 0.7 dB below the vacuum level. We achieve this in a triply resonant, pulsed electro-optic interconnect working in a millikelvin environment [5]. Our modular system produces itinerant microwave and optics photons and, thus, can be readily integrated in a quantum network with computational, repeater and memory nodes working in the gigahertz domain.

References

[1] Horodecki, R., Horodecki, P., Horodecki, M. & Horodecki, K. Quantum entanglement. *Reviews of Modern Physics* **81**, 865–942 (2009). Publisher: American Physical Society.

[2] Kimble, H. J. The quantum internet. *Nature* **453**, 1023–1030 (2008).

[3] Yoneda, J. *et al.* A quantum-dot spin qubit with coherence limited by charge noise and fidelity higher than 99.9%. *Nature Nanotechnology* **13**, 102–106 (2018). Number: 2 Publisher: Nature Publishing Group.

[4] Arute, F. *et al.* Quantum supremacy using a programmable superconducting processor. *Nature* **574**, 505–510 (2019). Number: 7779 Publisher: Nature Publishing Group.

[5] Sahu, R. *et al.* Quantum-enabled operation of a microwave-optical interface. *Nature Communications* **13**, 1276 (2022). Number: 1 Publisher: Nature Publishing Group.

High-efficiency and fast photon-number-resolving SNSPD [redacted]

Lorenzo Stasi[1,2], **Gaëtan Gras**[1], **Matthieu Perrenoud**[2], **Riad Berrazouane**[1], **Hugo Zbinden**[2] **and Félix Bussières**[1]

[1] *ID Quantique SA, CH-1227 Carouge, Switzerland*
[2] *Group of Applied Physics, University of Geneva, CH-1211 Geneva, Switzerland*

Photon-number resolving (PNR) single-photon detectors are an enabling technology in many areas such as photonic quantum computing, non-classical light source characterisation and quantum imaging [1, 2]. Here, we demonstrate high-efficiency PNR detectors using an array of parallel superconducting nanowire single-photon detector (P-SNSPD) [3] where the pixels (the single SNSPD element in the array) are connected in parallel to a single coaxial line, and the signal's amplitude informs on the number of pixels that clicked. To fully understand the PNR performances of the detector, we develop a model that can allow one to map the input statistics $S(m)$ of the light to the output signals produced by the device $Q(n)$: $Q(n) = \sum_{m=0}^{\infty} P_{nm} \cdot S(m)$, where P_{nm} represent the probability to detect n-photons if m-photons are arriving on it. Our model is based on evaluating the possible combinations of clicking pixels, but we do not make any prior assumption on the efficiencies of the single pixels and neither the spacial light distribution on them. Even though we do not have direct access to the single pixel efficiencies, we are able to retrieve them.

We present a 4-pixel P-SNSPDs using the process outlined in Ref. [4] which prevents both thermal and electrical crosstalk between the pixels and latching at high counting rate. We report a 92% efficiency P-SNSPD with fast recovery time (more than 60% nominal efficiency after 10 ns and 100% in 40 ns). The fidelity probabilities, namely the probability to correctly evaluate the incoming photon-number state are: $P_{11} = 92\%$, $P_{22} = 48.7\%$, $P_{33} = 9.2\%$ and $P_{44} = 0.6\%$. We also demonstrate how this detector allows reconstructing the photon-number statistics of a coherent source of light, which paves the way towards the characterisation of the photon statistics of other types of light source using a single detector.

References

1. Slussarenko, S. & Pryde, G. J. Photonic quantum information processing: A concise review. *Applied Physics Reviews* **6,** 041303 (2019).

2. Knill, E., Laflamme, R. & Milburn, G. J. A scheme for efficient quantum computation with linear optics. *nature* **409,** 46–52 (2001).

3. Marsili, F. *et al.* Superconducting parallel nanowire detector with photon number resolving functionality. *Journal of Modern Optics* **56,** 334–344 (2009).

4. Perrenoud, M. *et al.* Operation of parallel SNSPDs at high detection rates. *Superconductor Science and Technology* **34,** 024002 (2021).

Quantum variational learning for entanglement witnessing [redacted]

F. Scala[1], S. Mangini[1], C. Macchiavello[1], D. Bajoni[2], D. Gerace[1]

[1] *Università degli Studi di Pavia, Dipartimento di Fisica*
[2] *Università degli Studi di Pavia, Dipartimento di Ingegneria Industriale e dell'Informazione*

Several proposals have been recently introduced to implement Quantum Machine Learning (QML) algorithms for the analysis of classical data sets employing variational learning means. There has been, however, a limited amount of work on the characterization and analysis of quantum data by means of these techniques, so far. Besides representing a resource for QML, entanglement is also a property of quantum states that is usually difficult to characterise, as it requires a high number of measurements in order to be quantified via quantum tomography, and in this respect QML algorithms could offer an advantage over costly measurement procedures. This work focuses on one such ambitious goal, namely the potential implementation of quantum algorithms allowing to properly classify quantum states defined over a single register of n qubits, based on their degree of entanglement. As already mentioned, this is a notoriously hard task to be performed on classical hardware, due to the exponential scaling of the corresponding Hilbert space as 2^n.

In particular, we analyse a class of quantum states widely employed in quantum computing and quantum information, the *hypergraph states* [1], exploiting the notion of *entanglement witness* [2], *i.e.*, an operator whose expectation values allow to identify certain specific states as entangled. After the efficient implementation of an exact entanglement witness, we make use of Quantum Neural Networks (QNNs) and Variational Quantum Algorithms (VQAs) in order to successfully *learn* how to reproduce the action of the witness in a supervised learning fashion. More in detail, here we implement a hybrid quantum-classical algorithm allowing to learn an approximate (known and unknown) projective entanglement witness [1], through the use of a recently introduced quantum perceptron algorithm [3], [4].

This work may pave the way to an efficient combination of QML algorithms and quantum information protocols, possibly outperforming classical approaches to analyse quantum data.

References

[1] M. Ghio *et al.*, "Multipartite entanglement detection for hypergraph states," *Journal of Physics A: Mathematical and Theoretical*, vol. 51, no. 4, p. 045 302, 2017.

[2] M. Horodecki *et al.*, "Separability of mixed states: Necessary and sufficient conditions," *Physics Letters A*, vol. 223, no. 1, pp. 1–8, 1996.

[3] F. Tacchino *et al.*, "An artificial neuron implemented on an actual quantum processor," *npj Quantum Information*, vol. 5, no. 1, 2019.

[4] F. Tacchino *et al.*, "Variational learning for quantum artificial neural networks," *IEEE Transactions on Quantum Engineering*, vol. 2, pp. 1–10, 2021.

VCQ 2022 Summer School [redacted]
Observing single-particles beyond the Rindler horizon

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[2]*Institute for Complex Systems (ISC-CNR), Department of Physics, University Sapienza, Piazzale Aldo Moro 2, 00185, Rome, Italy*
[3]*Research Center Enrico Fermi, Via Panisperna 89a, 00184 Rome, Italy*

We show that Minkowski single-particle states localized beyond the horizon modify the Unruh thermal distribution in an accelerated frame [1]. This means that, contrary to classical predictions, accelerated observers can reveal particles emitted beyond the horizon. The method we adopt is based on deriving the explicit Wigner characteristic function for the complete description of the quantum field in the non-inertial frame [2] and which can be generalized to general states [3].

The origin of the predicted phenomena comes from an unique identity related to the Minkowski vacuum state: destroying a Rindler particle over the Minkowski vacuum in one wedge is equivalent to creating a particle in the other wedge. By following the method of [4, 5], we show that this result does not violate causality: no super-luminal communication between a right-Rindler observer and a left-Rindler observer holds.

References

[1] R. Falcone and C. Conti, "Observing single particles beyond the rindler horizon," 2022, arXiv:2205.03312 [gr qc].

[2] J. S. Ben Benjamin, M. O. Scully, and W. G. Unruh, "Transforming quantum states between reference frames," *Phys. Scr.*, vol. 95, p. 074015, Jun 2020.

[3] R. Falcone and C. Conti, "Minkowski-Fock states in Rindler space-time," to be published in *Phys. Rev. D.*

[4] E. Martín-Martínez, "Causality issues of particle detector models in qft and quantum optics," *Phys. Rev. D*, vol. 92, p. 104019, Nov 2015.

[5] J. de Ramòn, M. Papageorgiou, and E. Martín-Martínez, "Relativistic causality in particle detector models: Fasterthan-light signaling and impossible measurements," *Phys. Rev. D*, vol. 103, p. 085002, Apr 2021.

P1 Poster Session: Tuesday

VCQ 2022 Summer School [redacted]
All-fiber Dynamically Tunable Beamsplitter for Quantum Random Number Generators

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For cryptographic applications it is not sufficient that random numbers are generated with high entropy, it is also desirable to be able to certify that the random number generator has not been tampered with by an adversary. True random numbers are a scarce resource, and quantum random number generators (QRNGs) are able to overcome the limitations of deterministic machines through the inherent randomness in quantum mechanical projective measurements. However, QRNGs are prone to detector-side side-channel attacks, either by an adversary post-deployment or already at the manufacturing stage [2].

Novel measurement device-independent (MDI) protocols loosen the hardware requirements of fully device independent schemes while still allowing for certification of the system given some assumptions [2, 3]. In MDI the user is in control of the the state preparation while the measurement device is untrusted. Whenever the user wants to assert that the measurement device is operational, the user prepares and measures either of the orthogonal states which are expected to yield deterministic output, from which it is possible to bound the amount of information that could have leaked to an adversary. Testing the system disrupts randomness generation and the bitrate is lowered with an increased amount of test states being prepared and measured in lieu of states used for random number generation, further motivating the need for fast switching.

In this work we show a tunable beamsplitter based on a Sagnac interferometer that demonstrates exceptional stability over 42 hours as we generate data that, following randomness extraction, pass the widely-adopted NIST 800-22 test suite [1]. We also show that we are able to dynamically switch between preparing states necessary for device testing, and superposition states for randomness generation with high contrast. This work, using all-fiber commercial telecommunication components, enables integration with existing telecommunications networks and opens up for fast self-testing of communication systems that incur low overhead costs.

References

[1] Joakim Argillander, Alvaro Alarcón, and Guilherme B Xavier. *Journal of Optics* 24 (2022). DOI: 10.1088/2040-8986/ac68f4.

[2] Miguel Herrero-Collantes and Juan Carlos Garcia-Escartin. *Rev. Mod. Phys.* 89.1 (2017). DOI: 10.1103/RevModPhys.89.015004.

[3] You-Qi Nie et al. *Phys. Rev. A* 94 (2016). DOI: 10.1103/PhysRevA.94.060301.

VCQ 2022 Summer School [redacted] Abstract Template

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Many research groups are working to develop quantum computers using different technologies like trapped ions, superconducting circuits, photonics, etc. Among those techniques, trapped ions quantum computer is an encouraging way to realize a universal quantum processor. H. Hahn *et al.* demonstrated the experimental realization of a two-qubit Mølmer–Sørensen(MS) gate with a measured gate fidelity of $98.2 \pm 1.2\%$, limited by technical imperfections. They have extensively studied the source of error for the MS gate. Among the source of errors, a maximum of 1% infidelity comes from motional mode instability. Moreover, M Duwe *et al.* studied a numerical optimization method of a pulse envelope for amplitude modulation in Mølmer–Sørensen entangling gates where infidelity less than 1% was achieved. We numerically analyze quantum noise based on Kraus operator formalism for the MS gate to know how the noise affects the qubits. This helps us to characterize dominant noise channels, which can be suppressed later by using error mitigation techniques, tuning experimental parameters, etc. Furthermore, In particular, by taking into account the experimental restrictions, we also focus on increasing the fidelity by optimizing the tunable parameters.

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References

[1] H. Hahn *et al.* , et al.Integrated ^{9}Be+ multi-qubit gate device for the ion-trap quantum computer, npj Quantum Inf 5,**70**, (2019).

[2] M Duwe *et al.*, Numerical optimization of amplitude-modulated pulses in microwave-driven entanglement generation 2022 Quantum Sci. Technol. 7 045005

[redacted]

Quantum probes for many-body systems

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The key ingredient for understanding many-body systems when performing quantum simulations is an efficient readout of the available information. In quantum systems every extraction of information implies a backaction altering the system's state. Here, we present the first steps towards new quantum-limited probes for many-body quantum systems.

For our experimental studies we use one-dimensional Bose-Einstein condensates on an atomchip combined with spatially resolved measurements. We present an overview of the experimental setup located at the Atominstitut at TU Wien. Key to our studies is a fluorescence detection scheme with which we detect atoms with near unit efficiency.

We implement new probing schemes by employing global as well as local fields for outcoupling a controllable number of atoms. The controlled outcoupling allows us to tune the strength of the perturbation and we thus can study the influence of the measurement backaction.

VCQ 2022 Summer School [redacted]
Time ordering and quantum clocks

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In recent works, causality was assumed to be subjected to quantum indefiniteness [2]. Within the framework of process matrices [5], resources incompatible with the definite order of quantum operations were introduced. Causally non-separable processes were proven to exist by means of so-called "causal witnesses" [1][6]. In our work, we investigated the indefiniteness of time ordering by considering the time ordering operator in several different, albeit related contexts: (1) as it appears in the Schrödinger solution of standard quantum mechanics with time-dependent Hamiltonian, (2) in timeless quantum mechanics formalism, considering a constraint equation with several quantum clocks [3] and (3) in the context of quantum field theory and Feynman propagator. The motivating question was whether one can understand the action of the time ordering operator as enabling a superposition of different time ordered configurations, introducing time indefiniteness in the aforementioned settings. Regarding quantum fields, we questioned the possibility of the operational interpretation of the (scattering theory) virtual particle exchange process, often understood in terms of two time ordered processes happening via particle/antiparticle exchange [4]. Our approach was to look at the time-ordered exponentials up to the second order and attempt to isolate one of the ordering 'branches,' projecting a superposition to a definite state. We found that one cannot break the time ordering superposition of the exponential expansion in the context of standard quantum mechanics coupling it with the ancilla potential; however, one can perform this kind of projection in the context of timeless quantum mechanics with two or more quantum clocks. We then approached these considerations in the context of quantum fields, using the Schrödinger functional representation and timeless formalism.

References

[1] Mateus Araújo, Cyril Branciard, Fabio Costa, Adrien Feix, Christina Giarmatzi, and Časlav Brukner. "Witnessing causal nonseparability". In: *New J. Phys.* (2015).

[2] Časlav Brukner. "Quantum causality". In: *Nature Physics* (2014).

[3] Esteban Castro-Ruiz, Flaminia Giacomini, Alessio Belenchia, and Časlav Brukner. "Quantum clocks and the temporal localisability of events in the presence of gravitating quantum systems, Nature communications". In: (2020).

[4] Richard P. Feynman. *The reason for antiparticles.* Cambridge University Press, 2014.

[5] O. Oreshkov, F. Costa, and Č. Brukner. "Quantum correlations with no causal order". In: *Nat. Commun.* (2012).

[6] Giulia Rubino, Lee A. Rozema, Adrien Feix, Mateus Araújo, Jonas M. Zeuner, Lorenzo M. Procopio, Časlav Brukner, and Philip Walther. "Experimental verification of an indefinite causal order". In: *Sci. Adv.* (2016).

Enhanced Bell-state measurement with linear optics

[redacted]

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Bell-state measurements play an important role in many quantum technologies, e.g. in quantum repeaters, certain quantum communication protocols and photonic quantum computing. However, using linearoptics only, such a Bell-state measurement has a success probability of 50overcoming this limit. We give details on the experimental setup. We show how we generate Bell-states in a linear Mach-Zehnder-like scheme as well as how we create ancilliary N00N states from single photons. Both states interfere in a linear-optical setup and photon-number measurements at the output allow determining the respective Bell state.

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VCQ 2022 Summer School [redacted]
Experimental Certification of Quantum Transmission via Bell Theorem

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Quantum transmission links are one of the basic components in a standard setup for quantum information protocols. Emerging progress in developing quantum technologies should be followed with appropriate certification tools. In adversarial scenarios, a certification method can be vulnerable to attacks if we put too much trust in the underlying system. In this work, we consider certification of practical quantum transmission links in scenarios where little assumptions are made about the functioning of the whole setup used for certification. There are three main distinctive features of our work as compared to the previous contributions. Firstly, we completely abandon the assumption of independent and identically distributed samples (IID), which is known to be incompatible with cryptographic applications. Secondly, our method allows to estimate the quality of an actual transmission instead of a verification of a channel only. And finally, we consider the realistic scenario in which transmission losses are unavoidable by modelling a quantum transmission link as a completely-positive trace-decreasing map. We also provide preliminary results on a proof-of-principle experiment, relying on photon-pairs entangled in polarization, in order to show the feasibility of this protocol with current technology.

Diffracting Molecular Matter-Waves at a Standing Wave Light Grating in the Deep UV

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Light gratings are a highly versatile and powerful tool in matter-wave diffraction. While in atom interferometry the laser wavelength can be tuned close to an atomic resonance, the complex internal structure of molecules hampers this approach in high-mass interference. Instead, optical gratings in molecular interferometry build on pulsed gratings [1] or intense continuous wave laser light at 532 nm [2–4].

Here, we demonstrate single-grating diffraction of molecular matter waves at a continuous wave grating in the deep UV regime. Combining an external doubling cavity with a frequency-doubled Nd:YAG laser, we generate the fourth harmonic at 266 nm with an output power of up to 1.3 W. The standing light wave grating is then generated by retro-reflecting the light from a mirror in high vacuum. With this setup, we observe stable performance of the laser grating over time scales of over 5 hours. This is sufficient to realize first single-grating diffraction experiments with large organic molecules in the UV. Interestingly, we observe no contamination-induced degradation of the mirror in high vacuum, despite the short laser wavelength.

Compared to diffraction at 532 nm, this leads to a wider spacing of the diffraction orders. The deep UV diffraction grating opens the door to studying photoinduced and photochemical processes of biologically and technologically relevant molecules, while simultaneously exploring new grating mechanisms for matter-wave physics and applications such as high-mass cluster interferometry.

References

1. Haslinger, P. *et al.* A Universal Matter-Wave Interferometer with Optical Ionization Gratings in the Time Domain. *Nature Physics* **9,** 144–148 (2013).
2. Nairz, O., Brezger, B., Arndt, M. & Zeilinger, A. Diffraction of Complex Molecules by Structures Made of Light. *Physical Review Letters* **87,** 160401 (2001).
3. Gerlich, S. *et al.* A Kapitza–Dirac–Talbot–Lau Interferometer for Highly Polarizable Molecules. *Nature Physics* **3,** 711–715 (2007).
4. Brand, C. *et al.* Bragg Diffraction of Large Organic Molecules. *Physical Review Letters* **125,** 033604 (2020).

Hacking Quantum Key Distribution based on Quantum Dots

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Quantum Key Distribution (QKD) allows two remote parties to establish a private key over a public channel, assuming only the validity of quantum theory. While the security of QKD is in principle guaranteed by the uncertainty principle, real-world quantum systems are vulnerable to *side-channel* attacks exploiting the internal structure of classical or quantum devices [1, 2]. Recently, there has been growing interest in the implementation of QKD with quantum dot single-photon sources, thanks to their high brightness and low multiphoton emission. Here, we show that unlike their weak coherent state counterparts, these new sources are vulnerable to Trojan Horse-type attacks exploiting the inherent setup structure of phonon-assisted excitation. The adversary introduces weak coherent pulses in the source setup and analyses the signal performing a Beam Splitting Attack [3]. We highlight that standard countermeasures such as Decoy States [4] to probe channel losses and auxiliary detectors to monitor the incoming signal are not applicable in this scenario without lowering the secure key rate. We experimentally implement the attack on a setup based on InAs/InGaAs/GaAs dots, emitting in telecommunication C-band and excited via phonon assisted excitation [5].

References

[1] Lydersen, L., Wiechers, C., Wittmann, C. *et al.* Hacking commercial quantum cryptography systems by tailored bright illumination. Nature Photon **4**, 686–689 (2010).

[2] N. Gisin, S. Fasel, B. Kraus *et al.*, Phys. Rev. A **73**, 022320 (2006).

[3] Bennett, C.H., Bessette, F., Brassard, G. *et al.* J. Cryptology **5**, 3–28 (1992).

[4] Hoi-Kwong Lo, Xiongfeng Ma, and Kai Chen, Phys. Rev. Lett. **94**, 230504 (2005).

[5] M. Cosacchi, F. Ungar *et al.*, Phys. Rev. Lett. **123**, 017403 (2019).

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Highly efficient holographic optical elements for cold neutron experiments [redacted]

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Neutrons, and in particular, long-wavelength neutrons, provide unique insights into matter, and can potentially answer undeciphered questions of fundamental physics. In order to promote science with cold neutrons, we create holographic optical elements (HOEs) with materials that have customized properties to fill the gap in optical components for this wavelength range.

We present our recent results investigating the diffraction properties of nanodiamond based nanoparticle-polymer composites (NPC) gratings. The structure is formed by holographic recording of a sinusoidal light interference pattern over a mixture of homogeneously dispersed blend of monomers, nanodiamonds, and a photo-initiator system.

Nanodiamonds have large coherent scattering length and almost zero absorption and incoherent scattering cross sections. The studied sample presents higher nanodiamond concentration, have a different blend of materials and have a smaller thickness compared to the ones previously studied[1]. The large modulation of the scattering length density (SLD) makes it possible to reach high diffraction efficiencies for relatively thin gratings, without having to deal with the drawbacks caused by increasing the thickness, such as high angular selectivity.

We report our progress on optimizing of the diffraction properties of nanodiamond based NPC gratings, which where investigated at a first instance by light diffraction, and then by very cold neutron (VCN) small angle neutrons scattering (SANS) experiments. The obtained results demonstrate a decay of the structure along its thickness, and the exhibited high diffraction efficiencies indicate an extremely large SLD modulation.

References

[1] Yasuo Tomita, Akihisa Kageyama, Yuko Iso, Koichi Umemoto, Atsushi Kume, Ming Liu, Christian Pruner, Tobias Jenke, Stephanie Roccia, Peter Geltenbort, Martin Fally, and Jürgen Klepp. Fabrication of nanodiamond-dispersed composite holographic gratings and their light and slow-neutron diffraction properties. *Phys. Rev. Appl.*, 14(4):1, 2020.

[redacted] Generating four-photon GHZ states in the telecom wavelength regime using sagnac interferometer type sources

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Greenberger-Horne-Zeilinger (GHZ) states with multiple qubits are an important resource for quantum computation and quantum communication. In particular, multipartite communication protocols between three or more parties can greatly benefit from maximally entangled N-qubit GHZ states. Examples are quantum secret sharing protocols [**1**], quantum conference key agreement [**2**] and secure quantum e-voting [**3**], all of which require a reliable generation of entangled N-qubit states. Therefore, the experimental generation of such states is of great importance, in particular, in the telecom wavelength regime in order to use existing and well established fiber networks. In this work, we investigate the generation of multipartite GHZ states using single photon sources based on spontaneous parametric down-conversion in ppKTP-crystals. The sources are operated in a sagnac interferometer type scheme that generates two-photon Bell states. Fusing multiple of those states at beam splitters then creates multipartite entangled states. These can then serve as the basis for implementing multipartite communication protocols.

References

[1] M. Hillery, V. Bužek and A. Berthiaume, Phys. Rev. A **59**, 1829 (1999).

[2] A. Pappa et al., PRX Quantum **1**, 020325 (2020).

[3] C. Qiu, S. Zhang, Y. Chang et al., Int J Theor Phys **60**, 1550-1555 (2021).

VCQ 2022 Summer School [redacted]

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The equivalence of charged particles in external magnetic fields and neutral atoms in rapidly rotating traps opens up new avenues to study quantum hall physics with ultracold atomic gases.

In order to access the microscopic level of strongly correlated states we build on our previously established experimental methods – the deterministic preparation of ultracold ^{6}Li few Fermion systems in low dimensions [1], as well as local observation of their correlation and entanglement properties on the single atom level [2].

Here, we present current experimental progress towards adiabatic preparation of deterministic mesoscopic Fermion systems in rapidly rotating optical potentials. We showcase the optical setup, in particular the generation of interfering a Gaussian and Laguerre-Gaussian mode to achieve rotation [3]. Moreover, we show first experimental results of the new setup.

References

[1] M. Holten et al. Nature 606 (2022)

[2] A. Bergschneider et al. Nat. Phys. 15 (2019)

[3] L. Palm et al. New J. Phys. 22 (2020)

VCQ 2022 Summer School [redacted]
Quantum Machine Learning and Quantum Artificial Intelligence

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Modern generation's technology is driving towards applications of Quantum Information(QI) in the fields of Machine Learning(ML) and Artificial Intelligence(AI). Quantum Machine Learning(QML)'s vitality lies in speedups for data analysis techniques using quantum algorithms. QML outperforms classical ML using the following methods: Quantum Machine Learning for linear algebraic problems, quantum principal component analysis, quantum support vector machines and kernel methods, quantum optimization and deep quantum learning. Quantum effects mainly Quantum coherence and entanglement are used by quantum computers for information processing. Quantum artificial intelligence could conduct researches and experiments autonomously in future beyond classical capabilities. In this review poster, I'll describe the main ideas, recent developments, and progress in a broad spectrum of research investigating quantum machine learning and quantum artificial intelligence.

References

[1] Jacob Biamonte, , Peter Wittek, Nicola Pancotti, Patrick Rebentrost, Nathan Wiebe Seth Lloyd, Nature volume **549**, (2017)

[2] Vedran Dunjko and Hans J Briegel 2018 Rep. Prog. Phys. 81 074001

VCQ 2022 Summer School [redacted]
Optimising Single Photon Emission from Quantum Dots for Cryptographic Protocols

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Quantum dot-based single-photon sources are remarkable candidates for quantum cryptography, as they can in principle emit deterministically, with high brightness and low multiphoton contribution. Many quantum dot-based experiments employ resonant excitation (RE) schemes [**1**] featuring a low excitation power, short decay time and high indistinguishability. However, resonantly excited photons exhibit coherence in the Fock-basis [**2**] and is was recently shown [**3**] that the coherence can be used by an adversary to gain more information from intercepted photons. Therefore, for most cryptography applications, RE should be avoided. Blue-shifting the pump laser results in a longitudinal acoustic (LA) phonon assisted excitation where the photon-number coherence is lost. In contrast to RE where the optimal pump wavelength and power are fixed by the binding energy and π-pulse condition, in LA assisted excitation both wavelength and power are parameters that can be optimised. As theoretically suggested in [**4**], the brightness and purity of the single photons are maximal for different excitation parameters. Thus, a trade-off between the two must be considered with respect to the application.
Here, we present the first experimental study of the dependence of brightness and purity on pump wavelength and power in LA excitation. Striving for quantum cryptography applications, we studied an InGaAs quantum dot emitting in the telecom C-band.

References

[1] Takemoto, K., Nambu, Y., Miyazawa, T. et al. Quantum key distribution over 120 km using ultrahigh purity single-photon source and superconducting single-photon detectors. Sci Rep **5**, 14383 (2015).

[2] Wein, S.C., Loredo, J.C., Maffei, M. et al. Photon-number entanglement generated by sequential excitation of a two-level atom. Nat. Photon. **16**, 374–379 (2022).

[3] Bozzio, M., Vyvlecka, M., Cosacchi, M. et al. Enhancing quantum cryptography with quantum dot single-photon sources. arXiv:2204.11734 (2022).

[4] Cosacchi, M., Ungar, F., Cygorek, M. et al. Emission-Frequency Separated High Quality Single-Photon Sources Enabled by Phonons. Phys. Rev. Lett. **123**, 017403 (2019).

VCQ 2022 Summer School [redacted]
Super noise-robust one-dimensional model without conventional symmetries

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One modern way to model material which possesses robustness to disorder and impurities is to construct this material with respect to symmetries to construct a topologically non-trivial case[1]. Thus, starting with the Su-Schrieffer-Heeger model, non-trivial topology was connected with chiral symmetry, after - with time-reversal symmetry, particle-hole symmetry or crystal symmetry[2], [3]. The presence and absence of these symmetries define 10 symmetry classes and the periodic table of topological insulators[4]. In case of that, models which seem topologically protected but not directly included in this periodic table could be a good example of hidden physics in models. Exemplarily, quasi-periodic one-dimensional (1D) chains could support edge states, which in contrast to the 1D nature of the chains can be described in two-dimensional parametric space by Chern numbers[5]. This work is dedicated to a one-dimensional periodic zigzag-like model with an absence of these three symmetries. Notwithstanding the last fact, the model can demonstrate edge states with robustness to the quite sufficient amplitude of uniformly distributed random disorder, staying well-localized on the edge and picked to certain energy. The task of describing the topological origin of the model is challenging and requires a new technique for characterising of appearance nature of edge states.

References

[1] M. Z. Hasan and C. L. Kane. "Colloquium: Topological insulators". In: *Rev. Mod. Phys.* 82 (4 Nov. 2010), pp. 3045–3067. DOI: 10.1103/RevModPhys.82.3045. URL: https://link.aps.org/doi/10.1103/RevModPhys.82.3045.

[2] Xiao-Liang Qi and Shou-Cheng Zhang. "Topological insulators and superconductors". In: *Rev. Mod. Phys.* 83 (4 Oct. 2011), pp. 1057–1110. DOI: 10.1103/RevModPhys.83.1057. URL: https://link.aps.org/doi/10.1103/RevModPhys.83.1057.

[3] B. Bradlyn B.J. Wieder, J. Cano, and et al. "Topological materials discovery from crystal symmetry". In: *Nat. Rev. Mater* 7 (3 Mar. 2022), pp. 196–216. DOI: 10.1038/s41578-021-00380-2. URL: https://doi.org/10.1038/s41578-021-00380-2.

[4] Alexei Kitaev. "Periodic table for topological insulators and superconductors". In: *AIP Conference Proceedings* 1134 (22 May 2009), pp. 1057–1110. DOI: 10.1063/1.3149495. URL: https://doi.org/10.1063/1.3149495.

[5] Yaacov E. Kraus et al. "Topological States and Adiabatic Pumping in Quasicrystals". In: *Phys. Rev. Lett.* 109 (10 Sept. 2012), p. 106402. DOI: 10.1103/PhysRevLett.109.106402. URL: https://link.aps.org/doi/10.1103/PhysRevLett.109.106402.

Development and Testing of Free-Space Optical Terminals for Daylight Inter-Modal Quantum Key Distribution [redacted]

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The emergence of the Quantum Internet will require the distribution of quantum keys between communicating parties employing a combination of free-space and fiber channels between them. In this experiment, we performed daylight Quantum Key Distribution (QKD) in a hybrid architecture consisting of three nodes: Nodes 1 and 2 formed a 600m-long free-space link over the urban area of Padova, while Nodes 2 and 3 are connected by a deployed fiber channel. Two QKD paradigms were studied: in the first, an inter-modal repeater (Node 2) routing the optical signal from a transmitter (Node 1) to a receiver (Node 2) was implemented. In the second, the intermediate node served as a receiver between two transmitters placed on Nodes 1 and 3.

In both cases, the reception in the free-space channel was based on the coupling to a Single-Mode Fiber (SMF), aided by an Adaptive Optics (AO) configuration, in order to spatially filter background noise and achieve daylight operation through atmospheric turbulence. A 1550 nm quantum signal was sent through the fiber channel and measured by the receiver, whilst for the free-space channel a set of different control signals were multiplexed with the quantum one before being emitted by the transmitting telescope. The free-space optical communication part consisted of two additional lasers for the Pointing, Acquisition, and Tracking (PAT) system: a 980 nm laser for the AO correction, and a 1545 nm laser that was used to monitor the coupling efficiency.

This proof-of-concept experiment was run for a total of four hours during which we managed to obtain an always positive Secret Key Rate (SKR) of 630 bps on average. Hence, our work demonstrated the technology readiness and feasibility of implementing hybrid QKD networks operating in daylight.

*These authors contributed equally to this work.

Towards Driving Quantum Systems with the Non-Radiating Near-Field of a Modulated Electron Beam [redacted]

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When manipulating quantum systems with electromagnetic radiation, the spatial resolution is usually constrained by the diffraction limit. To overcome this limitation, we have developed a fundamentally new approach, in which we attempt to coherently transmit electromagnetic excitation through the non-radiating near-field of a modulated electron beam. This could open a path to spectrally selective quantum control with nanoscale spatial resolution by exploiting the small de Broglie wavelength of electrons. In a proof of principle experiment we use a spatially modulated electron beam generated by a fast cathode ray tube from an analog oscilloscope to coherently drive the hyperfine levels of potassium [**1**]. To also show coherent manipulation of a solid state quantum system, we perform Electron Spin Resonance with a BDPA sample. In this experiment realization a microcoil is used to detect the decay of the excited spins. The deflection of the electron beam in two dimensions allows for creating painted potentials, e.g. to imitate polarized light in the microwave range.

References

[1] D. Rätzel, D. Hartley, O. Schwartz, and P. Haslinger, "Controlling Quantum systems with modulated electron beams", Phys. Rev. Research 3, 023247 (2021).

P2 Poster Session: Thursday

VCQ 2022 Summer School [redacted]
Improved Synthesis of Restricted Clifford+T Circuits

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In quantum information theory, the decomposition of unitary operators into gates from some fixed universal set is of great research interest. Since 2013, researchers have discovered a correspondence between certain quantum circuits and matrices over rings of algebraic integers [1, 2, 3, 4, 5]. For example, there is a correspondence between a family of restricted Clifford+T circuits and the group $\mathrm{O}_n(\mathbb{Z}[1/2])$ [1]. Therefore, in order to study quantum circuits, we can study the corresponding matrix groups and try to solve the constructive membership problem (CMP): given a set of generators and an element of the group, how to factor this element as a product of generators? Since a good solution to CMP yields a smaller decomposition of an arbitrary group element, it helps us implement quantum circuits using fewer resources.

Here, we consider CMP for the groups $\mathrm{O}_n(\mathbb{Z}[1/2])$, of n-dimensional orthogonal matrices with entries in $\mathbb{Z}[1/2]$; and $\mathcal{L}_n$, of n-dimensional orthogonal matrices of the form $M/\sqrt{2}^k$, where M is an integer matrix and $k \in \mathbb{N}$. Both groups arise in the study of quantum circuits and correspond to important classes of restricted Clifford+T circuits. In 2020, Amy et al. defined an exact synthesis algorithm that decomposes an element of $\mathrm{O}_n(\mathbb{Z}[1/2])$ or $\mathcal{L}_n$ into a product of $O(2^n k)$ generators [1]. In this talk, I will first describe an improved synthesis method that works in arbitrary dimensions and requires $O(n^2 k)$ generators. Then, I will introduce an alternative synthesis method, namely, a global synthesis algorithm. It works in dimensions 2, 4, and 8, and it requires $O(k)$ generators.

References

[1] Matthew Amy, Andrew N Glaudell, and Neil J Ross. "Number-theoretic characterizations of some restricted Clifford+ T circuits". In: *Quantum* 4 (2020), p. 252.

[2] Simon Forest et al. "Exact Synthesis of Single-Qubit Unitaries Over Clifford-Cyclotomic Gate Sets". In: *Journal of Mathematical Physics* 56.8 (2015). Also available from arXiv:1501.04944, p. 082201. DOI: 10.1063/1.4927100.

[3] Brett Giles and Peter Selinger. "Exact Synthesis of Multiqubit Clifford+T Circuits". In: *Physical Review A* 87 (3 2013). Also available from arXiv:1212.0506, p. 032332. DOI: 10.1103/PhysRevA.87.032332. arXiv: 1212.0506.

[4] Vadym Kliuchnikov, Dmitri Maslov, and Michele Mosca. "Fast and Efficient Exact Synthesis of Single-qubit Unitaries Generated by Clifford and T Gates". In: *Quantum Information & Computation* 13.7-8 (2013). Also available from arXiv:1206.5236, pp. 607–630. DOI: 10.26421/QIC13.7-8. arXiv: 1206.5236.

[5] Vadym Kliuchnikov and Jon Yard. "A Framework for Exact Synthesis". Preprint available from arXiv:1504.04350. Apr. 2015.

VCQ 2022 Summer School [redacted]

M. Maslov[1], **M. Lemeshko**[1], **A. Volosniev**[1]

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We study an impurity with a resonance level whose position coincides with the Fermi energy of the surrounding Fermi gas. An impurity causes a rapid variation of the scattering phase shift for fermions at the Fermi surface, introducing a new characteristic length scale into the problem. We investigate manifestations of this length scale in the self-energy of the impurity and in the density of the bath. Our calculations reveal a model-independent deformation of the density of the Fermi gas, which is determined by the width of the resonance. To provide a broader picture, we investigate time evolution of the density in quench dynamics, and study the behavior of the system at finite temperatures. Finally, we briefly discuss implications of our findings for the Fermi-polaron problem.

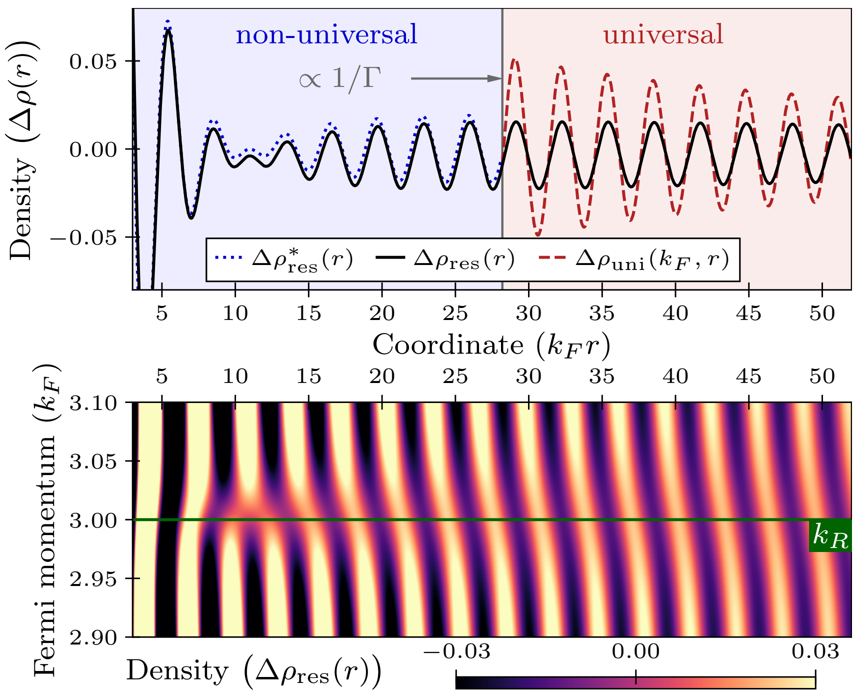

Figure 1: Spacial profile of the many-body density function: for an impurity with ($\rho_{\rm res}$) and without ($\rho_{\rm uni}$) an internal resonance. Density oscillations are deformed by the presence of an internal resonance level near the Fermi energy of the environment ($k_R \approx k_F$).

Can Variational Quantum Eigensolver calculate the ground energy of Hydrogen molecule in one million shots? [redacted]

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The Variational Quantum Eigensolver (VQE) can be used to find the ground state energy and the corresponding eigenstate of a Hamiltonian characterizing a molecular system. Even in the simplest implementations of VQE, many quantum computer calls (shots) are required in current implementations, and there is a lot of room for improvement. Due to two factors: the statistical nature of quantum measurement and the efficiency of the classical optimizer, the energies obtained at the end of the VQE method deviate from the real values. This compels one to repeat the experiment multiple times and chose the best value. Our work underlines the importance of precise energy calculation (Final checking) and the presence of an optimum between the number of shots and the final checking which helps in obtaining the desired results with greater probability. We put our research into practice using the hydrogen molecule as an illustration and demonstrate whether a million shots would be enough to obtain a reliable estimate of the ground state energy.

VCQ 2022 Summer School:

Solving rank constrained semidefinite programs in polynomial time

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We describe an iterative procedure that computes feasibility semidefinite programs over linearly constrained rank-one projectors. We prove that this rank constraint adds at most an $\mathcal{O}(n^3)$ factor to the complexity of the original problem before proceeding to demonstrate its application in currently open problems including unitary optimisation, unistochastic matrix classification, and a restricted version of the quantum marginal problem.

VCQ 2022 Summer School [redacted]

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Reducing the circuit depth of quantum circuits is a crucial bottleneck to enabling quantum technology. This depth is inversely proportional to the number of available quantum gates that have been synthesised. Moreover, quantum gate synthesis and control problems exhibit a vast range of external parameter dependencies, both physical and application-specific. In this article we address the possibility of learning families of optimal control pulses which depend adaptively on various parameters, in order to obtain a global optimal mapping from the space of potential parameter values to the control space, and hence producing continuous classes of gates. Our proposed method is tested on different experimentally relevant quantum gates and proves capable of producing high-fidelity pulses even in presence of multiple variables or uncertain parameters with wide ranges.

References

[1] F. Preti, T. Calarco, F. Motzoi, Continuous quantum gate sets and pulse class meta-optimization, arXiv:2203.13594.

VCQ 2022 Summer School [redacted] - Backend compiler phases for trapped-ion quantum computers

Tobias Schmale[1], Bence Temesi[1], Alakesh Baishya[1], Nicolas Pulido-Mateo[2,3], Ludwig Krinner[2,3], Timko Dubielzig[2], Christian Ospelkaus[2,3], Hendrik Weimer[1], Daniel Borcherding[1]

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A promising architecture for scaling up quantum computers based on trapped ions are so called Quantum Charged-Coupled Devices (QCCD). These consist of multiple ion traps, each designed for solving specific tasks, that are connected by transport links.

In this work we present the backend compiler phases needed for running quantum circuits on a QCCD architecture, while providing strategies to solve the optimization problems that occur when generating assembly instructions. We implement and test these strategies for the QVLS-Q1 chip architecture.

References

[1] T. Schmale et al., *Backend compiler phases for trapped-ion quantum computers*, IEEE International Conference on Quantum Software (QSW) (accepted), 2022, doi: 10.1109/QSW55613.2022.00020, arxiv: 2206.00544

Multiphoton interference with partially distinguishable photons

[redacted]

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The ability to interfere many single photons is a cornerstone for the development of photonic technologies as well as for demonstrations of quantum computational advantage via the Boson Sampling problem. An important source of noise in multiphoton interference experiments is that the input photons do not have perfectly identical wave-functions, i.e. they are *partially distinguishable*. We present different contributions regarding multiphoton interference with partially distinguishable photons. First, we show the counter-intuitive role of partial distinguishability in boson bunching phenomena, revealing how partially distinguishable photons may bunch more than indistinguishable ones [1]. Second, we present new tools for the efficient validation of boson samplers which can be used to distinguish whether the input photons are ideal bosons or partially distinguishable ones. Finally, we present the recently created Julia package BosonSampling.jl that regroups generic tools for the exploration of fundamental and practical questions about multiphoton interference with partially distinguishable photons [2].

References

[1] Seron Benoît, Leonardo Novo, and Nicolas J. Cerf. ”Boson bunching is not maximized by indistinguishable particles.”, Pre-print, arXiv:2203.01306 (2022).

[2] Seron Benoît, Antoine Restivo. ”BosonSampling.jl”, Julia Package, https://github.com/benoitseron/BosonSampling.jl

Rapid training of quantum recurrent neural network [redacted]

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Time series prediction is the crucial task for many human activities e.g. weather forecasts or predicting stock prices. One solution to this problem is to use Recurrent Neural Networks (RNNs). Although they can produce accurate predictions, their learning process is slow and complex.

In our work, we propose a Quantum Recurrent Neural Network (QRNN) to address these obstacles. The design of the network is based on the continuous-variable quantum computing paradigm [1]. In the regime of discrete variables similar algorithms exist and are also being investigated [2, 3], including hybrid quantum-classical models [4]. Those quantum algorithms have a demonstrable performance on sequence learning task and show the potential advantages of using quantum circuit for this task.

We demonstrate that our network is also capable of learning time dependence of a few types of temporal data. Our numerical simulations show that the QRNN converges to optimal weights in fewer epochs than the classical network. Furthermore, for a small number of trainable parameters, it can achieve a loss lower than that of the latter.

[1] Killoran, N., Bromley, T.R., Arrazola, J.M., Schuld, M., Quesada, N., Lloyd, S.: *Continuous-variable quantum neural networks.* Physical Review Research 1(3) (Oct 2019).

[2] Takaki, Y., Mitarai, K., Negoro, M., Fujii, K., Kitagawa, M.: *Learning temporal data with variational quantum recurrent neural network.* Physical Review A 103(5) (Dec 2020).

[3] Bausch, J.: *Recurrent Quantum Neural Networks.* In: Advances in Neural Information Processing Systems. vol. 33, pp. 1368–1379. Curran Associates, Inc. (2020)

[4] Chen SYC, Yoo S, Fang YLL. *Quantum Long Short-Term Memory.* In: ICASSP 2022 - 2022 IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP) pp. 8622–6. (2022).

VCQ 2022 Summer School [redacted]

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We report experimental progress in detecting Earths rotation with an optical fiber ring Sagnac interferometer using two-photon polarization-entangled NOON states of light. We have proposed and realized a fiber optic gyroscope which encodes the Sagnac phase in the polarization of light and performs polarization state tomography. Measurements with continuous-wave light have already verified that the sensitivity and stability levels of our fiber interferometer are sufficient to resolve a Earth rotation-induced phase shift of 3 mrad. By injecting NOON-states we aim to show super-resolution and work towards demonstrating quantum-enhancement in a large-scale interferometer [1]. This will also allow us to probe for the first time Earths rotation influence on photon entanglement, opening the door to proposed experiments using interferometry to measure frame dragging and other general-relativistic effects on quantum systems [2].

References

[1] M. Fink, F. Steinlechner, J. Handsteiner, J. P. Dowling, T. Scheidl, and R. Ursin, *Entanglement-enhanced optical gyroscope*, New J. Phys. **21**, 053010 (2019).

[2] A. J. Brady and S. Haldar, *Frame dragging and the hong-ou-mandel dip: Gravitational effects in multiphoton interference*, Phys. Rev. Res. **3**, 023024 (2021).

VCQ 2022 Summer School [redacted] Preliminary design and construction of a multi-port beamsplitter based on few-mode-fibers

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Secure communication has become more and more important these days and a way to ensure that the encryption keys are distributed in a secure way is to use Quantum Key distribution (QKD). This can be implemented by encoding the information to be sent onto the relative phase between two paths a single-photon can take, with the use of a beamsplitter [1]. A practical way to implement this scheme is to use superpositions between spatial modes in optical fibers [2], where the spatial modes in the fiber are different paths for the light to propagate. If one wants to extend this scheme to more than 2 spatial modes, thus enabling high-dimensional encoding, multi-port beamsplitters are needed. One design for this, could be the use of heterogeneous fiber structures, where optical fibers with different core sizes are spliced together. When doing so, multi-mode interference and self imaging occurs that can be used to excite different modes in the output fiber [3].

In this work, an all fiber multi-port beamsplitter was designed and constructed by splicing a multi-mode fiber between a single-mode fiber and a few-mode fiber. By doing this the spatial modes that can propagate in the few-mode fiber (LP_{01}, LP_{11a} and LP_{11b}) gets excited into superpositions and these have special spatial patterns that can be observed by using a infrared camera. In the results of this research, all the patterns of the spatial superpositions could be observed in the camera. Although the experimental patterns observed correspond very well to the simulated patterns, the conclusion of this work is that more experiments need to be performed in order to ensure that the patterns generated in fact are the real superpositons. Further research is also needed in order to see if this can be used for QKD.

References

[1] Gregor Weihs and Anton Zeilinger. "Photon statistics at beam splitters : an essential tool in quantum information and teleportation". In: *Coherence and statistics of photons and atoms*. Ed. by Jan Peřina. New York: Wiley, 2001. Chap. 1, pp. 262–288.

[2] A. Alarcón et al. In: *Physical Review Applied* 16 (3 Sept. 2021). DOI: `10.1103/PhysRevApplied.16.034018`.

[3] Nitin Bhatia and Joseph John. In: *Applied Optics* 53 (23 Aug. 2014). DOI: `10.1364/AO.53.005179`.

Quantum Simulations of Transverse Field Ising Models

[redacted]

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With the advancements in quantum technologies, it has become inevitable to investigate the potential existence of quantum advantages for quantum many-body systems. One of the most paradigmatic model is the transverse field Ising models (TFIMs) that can be simulated on a quantum computer to compute properties such as the ground-state energy. This problem, when tackled on a classical computer, leads to an exponential surge in the cost of computation with increasing system size. The advent of classical-quantum hybrid algorithms has shifted the focus to investigate the solution of the TFIMs using a unification of quantum and classical computers. One such algorithm, the Variational Quantum Eigensolver (VQE) algorithm [1], is considered reasonably good for obtaining the ground-state energy of quantum many-body systems in the current NISQ era. An efficient quantum simulation employs a good ansatz for the VQE algorithm that enables it to find a fairly good solution. Here we explore various ansätze, focusing mainly on the Hamiltonian variational ansatz [2], for calculating the ground-state energy of TFIMs. We devise strategies to compute the ground-state energy for different lattice geometries that are challenging to simulate on the current quantum hardware. In addition to that, we explore the quantum advantage and access the resource requirement for a quantum computer to evaluate the properties of systems in difficult regions around the quantum phase transition, which is a computationally difficult problem for a classical computer. Further, we extend our considerations to explore geometrically frustrated TFIMs using quantum simulation.

[1] A. Peruzzo, *et al.*, Nat. Comm. **5**, 4213 (2014).

[2] R. Wiersema, C. Zhou, Y. de Sereville, J. F. Carrasquilla, Y. B. Kim, and H. Yuen, PRX QUANTUM 1, 020319 (2020).

VCQ 2022 Summer School [redacted]
Classical Splitting of Parametrized Quantum Circuits

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Barren plateaus appear to be a major obstacle to using variational quantum algorithms to simulate large-scale quantum systems or replace traditional machine learning algorithms. They can be caused by multiple factors such as expressivity, entanglement, locality of observables, or even hardware noise. We propose classical splitting of ansätze or parametrized quantum circuits to avoid barren plateaus. Classical splitting is realized by splitting an N qubit ansatz to multiple ansätze that consists of $\mathcal{O}(\log N)$ qubits. We show that such an ansatz can be used to avoid barren plateaus. We support our results with numerical experiments and perform binary classification on classical and quantum datasets. Then, we propose an extension of the ansatz that is compatible with variational quantum simulations. Finally, we discuss a speed-up for gradient-based optimization and hardware implementation, robustness against noise and parallelization, making classical splitting an ideal tool for noisy intermediate scale quantum (NISQ) applications.

References

[1] C. Tüysüz, G. Clemente, A. Crippa, T. Hartung, S. Kühn, K. Jansen, Classical Splitting of Parametrized Quantum Circuits, arXiv: 2206.09641 (2022).

Entropic uncertainty relations and the quantum-to-classical transition

[redacted]

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Physics states the world is fundamentally quantum. Yet, this "quantumness" is not commonly perceived, as many quantum phenomena do not seem to be present in the macroscopic world. Moreover, there is an essential difference between classical and quantum descriptions: one cannot always prepare a quantum state with obserables A and B simultaneously well-defined. A natural question is how do we go from a quantum to a classical paradigm.

In this work, we study entropic uncertainty relations (EUR) [2]:

$$H(A|\Psi) + H(B|\Psi) \geq -2 \log \max_{j,k} | \langle a_j | b_k \rangle |, \tag{1}$$

$H(A|\Psi)$ is the Shannon entropy of measuring A on a state Ψ, and $|a_j\rangle$, $|b_k\rangle$ are eigenvectors of A, B. Classical behavior is achieved if this lower bound approaches zero as the system increases in size, meaning a state could have A and B simultaneously well defined (generally not allowed).

By analyzing X and Z, total magnetization observables in the directions x and z, we look for a model of macroscopic measurements that yields the desired behavior of the lower bound of the EURs.

To that end, we restrict the class of states we are considering to N-particle spin-coherent states $|\Psi\rangle^N = |\Psi_1\rangle^{\otimes N}$, known to saturate the EUR bound for X and Z [1]. Furthermore, we make the description of X and Z more realistic: we exploit the degeneracy of these measurements and also allow for imprecision, meaning we now measure the probability of Ψ having total magnetization falling inside some interval.

Considering these modifications, we get the expected behavior: the sum of entropies of measuring X and Z decreases with N, indicating that the quantities associated to these macroscopic measurements can be simultaneously well defined for a spin-coherent state.

In this work, we show that the inclusion of imprecision on macroscopic measurements is required to observe this classical character. Conversely, to preserve quantum features on large systems (like quantum computers), we indicate how precise measurements must be.

References

[1] FT Arecchi et al. "Atomic coherent states in quantum optics". In: *Physical Review A* 6.6 (1972), p. 2211.

[2] Hans Maassen and Jos BM Uffink. "Generalized entropic uncertainty relations". In: *Physical Review Letters* 60.12 (1988), p. 1103.

Enhancing quantum cryptography with quantum dot single-photon sources

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Quantum cryptography harnesses quantum light, in particular single photons, to provide security guarantees that cannot be reached by classical means. For each cryptographic task, the security feature of interest is directly related to the photons' non-classical properties. Quantum dot-based single-photon sources are remarkable candidates, as they can in principle emit deterministically, with high brightness and low multiphoton contribution[**1**, **2**]. In fact, source brightness is crucial in achieving high-speed quantum communication[**3**], while low multiphoton contribution minimizes information leakage to a malicious eavesdropper[**4**]. Here, we show that these sources provide additional security benefits, thanks to the tunability of coherence in the emitted photon-number states. We theoretically study three main optical pumping schemes of quantum dot cavity system (resonant excitation, phonon-assisted excitation and two-photons excitation), we identify the optimal optical pumping scheme for the main quantum-cryptographic primitives, and benchmark their performance with respect to Poisson-distributed sources such as attenuated laser states and down-conversion sources. In particular, we elaborate on the advantage of using phonon-assisted and two-photon excitation rather than resonant excitation for quantum key distribution and other primitives. The presented results will guide future developments in solid-state and quantum information science for photon sources that are tailored to quantum communication tasks.

References

[1] P. Michler, Quantum Dots for Quantum Information Technologies, Springer International Publishing (2017).

[2] Senellart, G. Solomon, and A. White, Nat. Nanotech. 12, 1026 (2017).

[3] A. Boaron, G. Boso, D. Rusca, C. Vulliez, C. Autebert, M. Caloz, M. Perrenoud, G. Gras, F. Bussières, M.-J. Li, et al., Phys. Rev. Lett. 121, 190502 (2018).

[4] G. Brassard, N. Lütkenhaus, T. Mor, and B. C. Sanders, Phys. Rev. Lett. 85, 1330 (2000).

See you next time!