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BACHELORARBEITEN SS 2019 – THEMENLISTE

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- Neutrino production from photomeson interactions in extragalactic jets

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- The positivity problem in quantum many-body systems
- Matrix Product States and their continuous generalizations

Ass.-Prof. Dr. Wolfgang Lechner

- Adiabatic Quantum Computing

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o. Univ.-Prof. Dr. Peter Zoller

Quantum Optical Quantum Networks and Quantum State Transfer

Quantum networks consists of 'nodes', as small quantum computers, connected via 'quantum channels'. In a quantum optical implementation quantum computers can be realized with trapped ions with internal atomic states as quantum memory. In a quantum optical network we connect these quantum computers with optical fibers to transmit quantum states. Here an atom-light interface converts the 'stationary qubits' represented by ions to 'flying qubits' represented by photons propagating in optical fibers. This is interesting from the perspective of scaling up quantum computers in a modular architecture. In this project we will focus on a theoretical description of quantum state transfer between the two nodes of the quantum network as the basic building block of quantum communication in a quantum network, and we are interested in simple quantum optical models representing this physics.

Literature:

[1] Kimble, H. Jeff. "The quantum internet." *Nature* 453, no. 7198 (2008): 1023-1030.
[2] Lodahl, P., Mahmoodian, S., Stobbe, S., Rauschenbeutel, A., Schneeweiss, P., Volz, J., Pichler, H. and Zoller, P., 2017. Chiral quantum optics. *Nature*, *541*(7638), pp.473-480.
[3] Gardiner, Crispin, and Peter Zoller. "The Quantum World of Ultra-Cold Atoms and Light Book II: The Physics of Quantum-Optical Devices." In *The Quantum World of Ultra-Cold Atoms and Light Book II: The Physics of Quantum-Optical Devices*, pp. 1-524. 2015.

Univ.-Prof. Dr. Thomas Franosch

Statistical physics of cluster formation in correlated nanomagnets

Artificial spin ice consists of arrays of lithographically patterned nanomagnets, where the shape of each magnet allows it to be represented as a single spin. With synchrotron based imaging techniques, the direction of each spin can be directly visualized. The magnets are arranged in lattice geometries such that there are competing interactions between neighboring spins, and all pairwise interactions cannot be simultaneously minimized. Such a system is said to be frustrated, and has similarities to water ice.

For suitably chosen lattice geometries, the local spin configurations take one of two forms, which coexist in equilibrium. Within a disordered configuration, locally ordered domains or clusters of these each of these types form. The size of these domains is dependent on the geometrical parameters and the temperature.

The analysis of cluster size distributions is a commonly used method to probe the universal statistics of systems near a phase transition, where the cluster sizes can follow a power law, with an exponent independent of the specifics of the system.

In this project we investigate the physics of artificial spin ice in equilibrium through analysis of the statistics of the formed clusters. The goal of the bachelor thesis is to apply a statistical analysis to the size, shape and distribution of clusters, and investigate the dependence on temperature and geometry.

References:

[1] Oleksandr Chepizhko, Costanza Giampietro, Eleonora Mastrapasqua, Mehdi Nourazar, Miriam Ascagni, Michela Sugni, Umberto Fascio, Livio Leggio, Chiara Malinverno, Giorgio Scita, et al. Bursts of activity in collective cellmigration. Proceedings of the National Academy of Sciences, 113(41):11408–11413, 2016.

[2] Oleksandr Chepizhko and Fernando Peruani. Active particles in heterogeneous media display new physics. The European Physical Journal Special Topics, 224(7):1287–1302, 2015.

[3] Alan Farhan, Charlotte F Petersen, Scott Dhuey, Luca Anghinolfi, Qi Hang Qin, Michael Saccone, Sven Velten, Clemens Wuth, Sebastian Gliga, Paula Mellado, et al. Nanoscale control of competing interactions and geometrical frustration in a dipolar trident lattice. Nature communications, 8:995, 2017.

[4] RF Wang, C Nisoli, RS Freitas, J Li, W McConville, BJ Cooley, MS Lund, N Samarth, C Leighton, VH Crespi, et al. Artificial ’spin ice’ in a geometrically frustrated lattice of nanoscale ferromagnetic islands. Nature, 439(7074):303–306, 2006.

Effect of defects on emergent magnetic monopoles in lattices of nanomagnets

Artificial spin ice consists of arrays of lithographically patterned nanomagnets, where the shape of each magnet allows it to be represented as a single spin. With synchrotron based imaging techniques, the direction of each spin can be directly visualized. The magnets are arranged in a lattice where spins meet at vertices, such that there are competing interactions between neighboring spins, and all pairwise interactions cannot be simultaneously minimized. Such a system is said to be frustrated, and has similarities to water ice. With an appropriate choice of geometry, the preferred arrangement of spins follow a so called "ice-rule", which determines the ordering. In this state, the number of spins pointing into a vertex is equal to the number pointing out of a vertex. In equilibrium, exceptions to this rule occur, resulting in unbalanced vertices, which can be considered to have a magnetic charge. These are also referred to as emergent magnetic monopoles.

Real artificial spin ice systems are constrained by the limitations of lithography techniques, which introduces defects in the nanomagnets. These defects may affect the creation and dynamics of the emergent magnetic monopoles. In this project we consider the effect of defects in the lattice on the emergent magnetic monopoles in artificial spin ice. The goal of the bachelor thesis is to investigate through computer simulations how systematic changes to the nanomagnet properties change the dynamics.

References:
[1] Yann Perrin, Benjamin Canals, and Nicolas Rougemaille. Extensive degeneracy, coulomb phase and magnetic monopoles in artificial square ice. Nature, 540(7633):410, 2016.
[2] RF Wang, C Nisoli, RS Freitas, J Li, W McConville, BJ Cooley, MS Lund, N Samarth, C Leighton, VH Crespi, et al. Artificial 'spin ice' in a geometrically frustrated lattice of nanoscale ferromagnetic islands. Nature, 439(7074):303–306, 2006.

Univ.-Prof. Mag. Dr. Helmut Ritsch

Quantenoptik Simulationen mit der Julia Quantum Optics Toolbox

Julia is an open source programming language developed at MIT allowing efficient and easy to read framework for physics simulations. The additional package qojulia (https://www.qojulia.org/) developed in Innsbruck allows effective implementations of typical quantum optics Hamiltonians in Julia. This should be demonstrated in a generic example in this thesis.

A laser as a quantum model of a heat engine

A single mode laser can be seen as a heat engine converting high temperature thermal radiation to a single mode coherent field of vanishing entropy. At the hand of a single or a few three level atoms coupled to thermal reservoirs and a cavity mode, the underlying concepts should be explained and the efficiency and power of the operation studied.

[1] Boukobza, E., and H. Ritsch, Physical Review A 87.6 (2013): 063845.

Univ.-Prof. Dr. Oriol Romero-Isart

Light scattering by a dielectric nanosphere

The interaction of light and matter lies at the root of many processes in nature. Studying, understanding, and exploiting these processes has been one of the main goals of science in the past centuries. One prominent example is the invention of the laser that is based on the process of stimulated emission. Another example, that is usually studied in the framework of classical and macroscopic electromagnetism, is the scattering of an electromagnetic plane wave by a homogenous dielectric sphere. The precise understanding of the dynamics together with the ability of measuring the relevant degrees of freedom of the scattered light in a controlled way allows to estimate properties of the dielectric sphere. This measurement technique is nowadays a standard technique used in many experiments.

In this project the student will rederive Mie solutions for a dielectric sphere [1]. In addition, the student will derive the eigenmodes of Maxwell equations in presence of a dielectric sphere in order to quantize the theory [2].

[1] C. F. Bohren and D.R. Huffman, Absorption and Scattering of Light by Small Particles (Wiley-VCH, 1998)
[2] R. J. Glauber and M. Lewenstein, Quantum Opicts of Dielectric Media, Phys. Rev. A, 43, 467 (1991).

Brownian dynamics and path integrals

The understanding of the time evolution of quantum systems interacting with an environment (usually called open systems) is of fundamental interest [1]. Usual theoretical methods rely on the assumption that the system at each time has no information of its past evolution, which is in agreement with most of the phenomenology studied in the Literature. In these cases, it is said that those processes is Markovian [2]. However, there is a vast number of cases where this assumption does not work even as an approximation (non-Markovian processes).

One of the most paradigmatic examples that under different conditions can give both Markovian or non-Markovian behaviours is the quantum brownian motion, consisting in a particle interacting with a reservoir (which is typically modelled as a set of N harmonic oscillators). The richness of this system complemented with its simplicity provides an unparalleled and fruitful scenario for understanding the physical concepts applicable for a broad variety of phenomenology. Beyond the mentioned techniques for Markovian dynamics, path integrals shown to be extremely useful for addressing all the possible scenarios in a unified and systematic way by the introduction of the Feynman-Vernon influence functional [3,4].

In this project the student will learn about these techniques and how to apply them to solve the quantum brownian motion. Exploring all the mentioned dynamical features for different number N of constituents of the reservoir will shed light on the origin of the concepts of dissipation and noise from a theoretical point of view.

[1] Breuer H.-P. and Petruccione F., “The theory of open quantum systems” (Oxford University Press, New York, USA, 2002).
[2] C. Cohen-Tannoudji, J. Dupont-Roc and G. Grynberg, “Atom-photon interactions: Basic processes and applications” (Wiley, UK, 1998).
[3] R. P. Feynman and A. R. Hibbs, “Quantum mechanics and path integrals” (McGraw-Hill, New York, 2010).
[4] E. A. Calzetta and B. L. Hu, “Nonequilibrium quantum field theory” (Cambridge University Press, Cambridge, England, 2008).

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Assoz. Prof. Mag. Dr. Wolfgang Dür

Messungsbasierte Quantenfehlerkorrektur

Quantenfehlerkerkorrektur ist ein zentrales Element der im Bereich des Quantenrechnens. Dabei wird Quanteninformation in kodierter Form gespeichert und manipuliert, wodurch sichergestellt wird, dass trotz Rauschens und Dekohärenz die quantenmechanischen Eigenschaften erhalten bleiben. Ein Ansatz verfolgt die Verwendung von Messungsbasierten Elementen in der Quantenfehlerkorrektur. Dabei werden bestimmte verschränkte Ressourcenzustände dazu verwendet, um Kodierung, Dekodierung und Fehlersyndrombestimmung alleinig durch Messungen durchzuführen. Dieses Verfahren ist dabei besonders robust gegenüber Rauschen und Imperfektionen. Ziel der Bachelorarbeit ist es, die zentralen Elemente dieses Zugangs zu erarbeiten, und eigenständig konkrete Beispiele (Fehlerkode, Ressourcenzustände) auszuarbeiten und zu untersuchen. Neben der theoretischen Behandlung sollen auch experimentelle Realisierungen mit gefangenen Ionen bzw. einzelnen Photonen diskutiert werden.

Literatur:

M. Zwerger, H.J. Briegel, W. Dür, Applied Physics B, 122:50 (2016)
(E-print: arXiv:1506.00985)
E. Knill, Nature 434, 39 (2005). (E-print: arXiv:0410199)
B. P. Lanyon et.al., Phys. Rev. Lett. 111, 210501 (2013). (E-print: arXiv:1308.5102)
Stefanie Barz et. Al, Phys. Rev. A 90, 042302 (2014).

Assoz. Prof. Mag. Dr. Barbara Kraus

Quantenfehlerkorrektur

Fehler treten in jeder quantenmechanischen Berechnung auf. Ohne die Möglichkeit diese Fehler zu korrigieren wäre eine quantenmechanische Berechnung nicht sehr nützlich. Ziel dieser Bachelorarbeit ist es Methoden zur Fehlerkorrektur zu erlernen.

Literatur:

[1] M. Nielsen, I. Chuang, Quantum Computation and Quantum Information, Cambridge, UK: Cambridge University Press

Verschränkungstheorie (2 Parteien)

Eine Funktion von einem Zustand ist ein Verschränkungsmaß, wenn sie gewisse Eigenschaften erfüllt. Zum Beispiel kann Verschränkung unter lokalen Operationen nicht erhöht werden. Für zwei Teilchen sind diese Maße relativ gut verstanden und es gibt viele verschiedene Beispiele von Verschränkungsmaßen.

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Ziel dieser Bachelorarbeit ist es die Bedeutung einiger Verschränkungsmaße zu verstehen und die Eigenschaften einiger Verschränkungsmaße auszuarbeiten.

Literatur:

[1] M. Nielsen, I. Chuang, Quantum Computation and Quantum Information, Cambridge, UK: Cambridge University Press

[2] R. Horodecki, P. Horodecki, M. Horodecki, K. Horodecki, Quantum entanglement, Rev.Mod.Phys.81:865-942, 2009

[3] G. Vidal, Entanglement monotones, J.Mod.Opt. 47 (2000) 355

Assoz. Prof. Dipl.-Phys. Dr. Anita Reimer

Neutrino production from photomeson interactions in extragalactic jets

Recent data from the IceCube Neutrino Observatory reveal the detection of extraterrestrial neutrinos at energies tens of TeV to a few PeV, however with large positional uncertainties. Among the most promising counterpart sources are extragalactic jets where neutrinos can be produced through strongly interacting protons with photons from the prominent radiative jet environment. Dermer, Murase & Inoue (2014) proposed a model to explain the observed PeV-neutrinos where neutrino spectra from photomeson production have been calculated analytically using a number of approximations.

The bachelor project consists of understanding neutrino generation via photomeson production in general and applied to cosmic jet sources. In a subsequent step the goodness of the approximations used in Dermer, Murase & Inoue (2014) shall be evaluated by comparing with corresponding Monte-Carlo calculations using a photomeson production event generator.

Requirements: Special Relativity; basics of particle physics

Literature:

C. Dermer & G. Menon, "High Energy Radiation from Black Holes: gamma-rays, cosmic rays and neutrinos", Princeton University Press, Chap. 2, 5, 9.

C. Dermer, K. Murase & Y. Inoue, Journal of High Energy Astrophysics, Volume 3, p. 29-40 (2014).

A. Mücke, R. Engel, J. Rachen, R. Protheroe, T. Stanev, Computer Physics Communications, vol. 124, Issue 2-3, pp.290-314 (2000).

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Ass.-Prof. Dr. Gemma De las Cuevas

The positivity problem in quantum many-body systems

The positivity problem in quantum many-body systems is the difficulty of representing a quantum mixed state efficiently. Namely, mixed states are described by positive semidefinite matrices. However, efficient representations of mixed states do not make the positivity of the state explicit [1,2], and this leads to many problems. Recently it was found that this problem is related to several other problems in mathematics, in particular to decompositions of nonnegative matrices [3]. In this work we will analyse several of these connections to gain insight into the positivity problem.

[1] G. De las Cuevas, N. Schuch, D. Perez-Garcia and J. I. Cirac, New J. Phys. 15, 123021 (2013).

[2] G. De las Cuevas et al, J. Math. Phys. 57, 71902 (2016).

[3] G. De las Cuevas and T. Netzer, The positivity problem in quantum many-body systems and matrix cones, upcoming.

Matrix Product States and their continuous generalizations

The description of quantum systems based on Hilbert spaces is not scalable, as the number of parameters grows exponentially with the system size. Tensor Networks are an ansatz to describe some quantum many-body states efficiently [1]. Matrix Product States are a particular case of this ansatz, where the states are defined on a one dimensional lattice [2], and have very fast decaying correlations. Continuous Matrix Product States are a continuous version of Matrix Product States [3]. Recently, it was seen that Continuous Matrix Product States should be generalized [4]. In this work we will study possible meaningful generalizations of this ansatz.

[1] R. Orus, Ann. Phys. 349, 117 (2014).

[2] D. Perez-Garcia, F. Verstraete, M. Wolf, J. I. Cirac, Quantum Inf. Comput. 7, 401 (2007).

[3] F. Verstraete and J. I. Cirac, Phys. Rev. Lett. 104, 190405 (2010).

[4] G. De las Cuevas, N. Schuch, D. Perez-Garcia and J. I. Cirac, Phys. Rev. B 98, 174303 (2018).

Ass.-Prof. Dr. Wolfgang Lechner

Adiabatic Quantum Computing

Das Ziel eines adiabatischen Quantencomputers ist es, quantenmechanische Eigenschaften wie Superposition, Verschränkung und Tunneln zu verwenden, um Optimierungsprobleme zu lösen. Dies können klassische Optimierungsprobleme sein (wie das Traveling Salesman Problem) oder quantenmechanische Probleme (wie Elektron-Grundzustände in Molekülen). In dieser Bachelorarbeit verwenden wir einen adiabatischen Quantencomputer, der auf einem Ising-model mit 4-Körper-Wechselwirkungen basiert. Diese bestimmte Art der Wechselwirkung kann dazu verwendet werden neue Protokolle zu entwickeln, die z.B. für künstliche Intelligenz relevant sind. Konkret soll in der Bachelorarbeit ein adiabatisches Protokoll entwickelt und optimiert werden. Aus den theoretischen Ergebnissen sollen Vorschläge für experimentelle Implementierungen entstehen.
Voraussetzung: gute Kenntnisse der Quantenphysik

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