universität
innsbruck

Institut für
Theoretische Physik

BACHELORARBEITEN SS 2018 – THEMENLISTE

o. Univ.-Prof. Dr. Peter Zoller

- Quantum Optical Quantum Networks and Quantum State Transfer

Univ.-Prof. Dr. Thomas Franosch

- Active particle with memory (subjected to colored noise)
- Disorder in models of artificial spin ice

Univ.-Prof. Dr. Andreas Läuchli

- Themen wurden bereits vergeben

Univ.-Prof. Mag. Dr. Helmut Ritsch

- Quantenoptik Simulationen mit der Julia Quantum Optics Toolbox
- Number factoring by finding ground states of spin systems

Univ.-Prof. Dr. Oriol Romero-Isart

- Phononic excitations of nanoscale solids
- Brownian dynamics and path integrals

Assoz. Prof. Mag. Dr. Wolfgang Dür

- Messungsbasierte Quantenfehlerkorrektur
- Quantenmetrologie

Assoz. Prof. Mag. Dr. Barbara Kraus

- Shannon Entropie
- Quantenkryptographie

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

- Neutrino production from photomeson interactions in extragalactic jets

Ass.-Prof. Dr. Wolfgang Lechner

- Adiabatic Quantum Computing

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

Active particle with memory (subjected to colored noise)

There has been an increasing interest in the study of self-propelled particles, that move by converting energy of the surroundings into directed motion. These active particles are abundant in nature such as bacteria and sperms, which propell themselves by a single or an array of flagella pushed by molecular motors. Recently, also artificial microswimmers have been synthesized experimentally and are expected to play a crucial role in nanotechnology.

These active agents move in an aqueous solution at low Reynolds number and are therefore subject to strong stochastic fluctuations, which compete with their directed swimming motion.

A commonly used method to describe the motion of these active particles is Langevin equations, where the particle moves along its instanteneous orientation, which is subject to noise. Usually, Brownian noise is considered, butmore realistic description may require the study of colored noise.

In this project we consider a particle subject to a colored noise and work out its influence on the particle's dynamics, which now will have memory. The goal of the bachelor thesis is to discuss the dynamical behavior of the active particle in terms of computer simulations and analytical computations.

References:

[1] Christina Kurzthaler and Thomas Franosch. Intermediate scattering function of an anisotropic Brownian circle swimmer. Soft Matter, 13:6396–6406, 2017.
[2] Jörg Nötel, Igor M. Sokolov, and Lutz Schimansky-Geier. Adiabatic elimination of inertia of the stochastic microswimmer driven by α-stable noise. Phys. Rev. E, 96:042610, Oct 2017.
[3] Jörg Nötel, Igor M Sokolov, and Lutz Schimansky-Geier. Diffusion of active particles with stochastic torques modeled as α-stable noise. Journal of Physics A: Mathematical and Theoretical, 50(3):034003, 2017.

Disorder in models of artificial spin ice

Artifcial 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. Recent advances in lithography techniques mean that thermally active artifcial spin ices can be fabricated. That is, the energy barrier to the spin fipping in direction is on the order of the thermal energy, so thermal fluctuations in the microscopic configurations can be directly imaged. This allows for detailed analysis of the dynamics.

A key feature of artificial spin ice is the ease with which it can be modeled and simulated, making it an ideal test-bed for theories developed in theoretical spin models. In the simplest case, all nanomagnets are modeled as identical spins. However, real artificial spin ice systems are constrained by the limitations of lithography techniques, which introduce disorder in the properties of each nanomagnet. This disorder can affect the physics of the system in interesting ways, and there are a number of possible approaches to introduce it into the model of the system.

In this project we consider the role of disorder in the thermal dynamics of artificial spin ice. The goal of the bachelor thesis is to investigate through computer simulations how the form the disorder takes affects the dynamics.

References:

[1] R. Wang, C. Nisoli, R. Freitas, J. Li, W. McConville, B. Cooley, M. Lund, N. Samarth, C. Leighton, V. Crespi, et al., “Artificial 'spin ice' in a geometrically frustrated lattice of nanoscale ferromagnetic islands”, Nature, vol. 439, no. 7074, pp. 303-306, 2006.
[2] A. Farhan, C. F. Petersen, S. Dhuey, L. Anghinolfi, Q. H. Qin, M. Saccone, S. Velten, C. Wuth, S. Gliga, P. Mellado, et al., “Nanoscale control of competing interactions and geometrical frustration in a dipolar trident lattice”, Nature communications, vol. 8, p. 995, 2017.
[3] K. Kohli, A. L. Balk, J. Li, S. Zhang, I. Gilbert, P. E. Lammert, V. H. Crespi, P. Schiffer, and N. Samarth, “Magneto-optical kerr effect studies of square artificial spin ice”, Physical Review B, vol. 84, no. 18, p. 180412, 2011.

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.

Number factoring by finding ground states of spin systems

Ground states of Hamiltonians for coupled spin systems can be designed to encode solutions of complex problems. This should be demonstrated at the example of number factoring in this project.

Univ.-Prof. Dr. Oriol Romero-Isart

Phononic excitations of nanoscale solids

Early experiments on quantum mechanics were often based on individual microscopic particles like electrons or photons. At the far end of the scale are macroscopic bulk solids, were quantum mechanics is for example evident in the conductivity of semiconductors. New and largely unexplored phenomena arise in at the intermediate, mesoscopic scale due to a large number of constituents combined with a finite size. It is becoming increasingly feasible to observe the quantum behavior of mesocale solids, like levitated nanospheres [1], and relevant to describe their interaction with other quantum systems, for example when trapping atoms close to optical fibers [2]. In all these systems, material vibrations play an essential role.

In this project, the student will learn how to describe quantized deformations (phonons) of a solid using linear elasticity theory [3]. The project will be structured as follows: 1. Classical theory, 2. Canonical quantization, 3. Bulk eigenmodes, 4. Eigenfrequency band structure of a nano-cylinder. The first three parts involve analytic calculations, part four numerical calculations. As an extension, the student may for example study the conserved quantities (like energy and angular momentum) of this field theory.

Besides covering the mechanics of deformable bodies, this project will provide a tangible primer on quantum field theory.

[1] O. Romero-Isart, A. C. Pflanzer, M. L. Juan, R. Quidant, N. Kiesel, M. Aspelmeyer, and J. I. Cirac: Phys. Rev. A 83, 013803 (2011)
[2] Fam Le Kien, S. Dutta Gupta, and K. Hakuta: Phys. Rev. A 75, 062904 (2007)
[3] J.D. Achenbach: “Wave Propagation in Elastic Solids”. North-Holland Publishing, Amsterdam (1973)

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).

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).

Quantenmetrologie

Die Bestimmung von physikalischen Größen mit möglichst großer Genauigkeit gehört zu den zentralen Problemen der Physik. Dabei geht es nicht nur um die Messung von Naturkonstanten, sondern auch die möglichst exakte Bestimmung von Frequenzen, Zeiten, Kräften oder Stärke von Magnetfeldern.

Die Quantenmetrologie beschäftigt sich mit der erzielbaren Genauigkeit von Messungen unter Berücksichtigung der Quantenmechanik. Dabei konnte gezeigt werden, dass quantenmechanische Verschränkung (bzw. allgemein die Ausnutzung von Quanteneffekten) eine quadratische Verbesserung der erreichbaren Präzession erlaubt. Ziel der Arbeit ist es, die Grundlagen der Quantenmetrologie zu verstehen und einfache Quantenmetrologie-protokolle (z.B. zur Frequenz- oder Phasenbestimmung) nachzuvollziehen. Darüber hinaus sollen Limitierungen auf Grund von Rauschen und Dekohärenz untersucht, und einfache Beispiele eigenständig behandelt werden.

Literatur:
V. Giovannetti, S. Lloyd, and L. Maccone, Science 306, 1330 (2004) (E-print: quant-ph/0412078)
Vittorio Giovannetti, Seth Lloyd, Lorenzo Maccone, Nature Photonics 5, 222 (2011)
(E-print: arXiv:1102.2318)
Géza Tóth and Iagoba Apellaniz, Journal of Physics A: Mathematical and Theoretical, Volume 47, Number 42 (2014)
P. Sekatski, M. Skotiniotis, J. Kolodynski and W. Dür, Quantum 1, 27 (2017).

Assoz. Prof. Mag. Dr. Barbara Kraus

Shannon Entropie

Die Shannon Entropie (und ihre Verallgemeinerungen) ist eine wesentliche Größe in der Informationstheorie. Shannon zeigt damit zwei fundamentale Ergebnisse in der Informationsverarbeitung und prägte damit die moderne Informationstheorie.

Ziel dieser Arbeit ist es die Eigenschaften der Shannon Entropie und einige ihrer Verallgemeinerungen und die 2 Theoreme, „noiseless coding theorem" und „noisy channel coding theorem" zu verstehen.

Literatur:

[1] M. Nielsen, I. Chuang, Quantum Computation and Quantum Information, Cambridge, UK: Cambridge University Press
[2] Lecture Notes for Physics 229: *Quantum Information and. Computation,* John Preskill. California Institute of Technology. September, 1998

Quantenkryptographie

Eine der faszinierenden Anwendungen der Quanteninformationstheorie liegt in der sicheren Verschlüsselung von Nachrichten. Sogenannte Quantum Key Distribution (QKD) Protokolle wurden entwickelt um einen sicheren

Schlüssel zwischen den legitimierten Parteien zu erzeugen, der dann für die Verschlüsselung der Nachricht verwendet werden kann.

Ziel dieser Arbeit ist es, das Prinzip der QKD anhand einiger Beispiele zu verstehen und die Sicherheit der Protokolle zu untersuchen.

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

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).

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