Exercise / Journal Club „Milestones of Quantum Technology I“

Institut: Institut für Optik und Atomare Physik, TU Berlin
Responsible persons: Janik Wolters, T. Heindel, A. Carmele
Email: janik.wolters@dlr.de

Dates and location:
Wednesday 16-18h (23.10., 30.10., 13.11., 20.11., 27.11., 4.12., 11.12., 18.12., 8.1., 15.1., 22.1., 29.1., 5.2., 12.2.)

Einstein Center Digital Future, Wilhelmstraße 67, Room RKF 009

Learning outcomes:

In this module the basic concepts, applications, and implementations of quantum technology are elaborated and discussed by the participants. The focus is on the understanding of the scientific topics on the basis of research articles. The module promotes independent scientific work in all fields of quantum technologies, with an emphasis on experimental and theoretical quantum optics.

Teaching content:

Milestones of Quantum Technology I (winter semester)

- Atoms in the vapor phase
- Semiconductor quantum dots
- Quantum key distribution
- Quantum computing with linear optics and trapped ions

Work load and credit points

Time of attendance: 15 x 2 h, preparation time: 15 x 4 h; Total: 45h ~ 3 LP (each)

Description of forms of teaching and learning

Exercise with one presentation and discussion per event date. The individual topics are worked out by all students at the hand of a question list.

Requirements for participation

The seminar is aimed at master and doctoral students in physics and related disciplines.

Examination

Grading: ungraded; Type of examination: no examination

The successful participation requires active presence during the whole exercise.

Duration of the modules:

1 semester each

Milestones of Quantum Technology I
WS19/20
J. Wolters, T. Heindel, A. Carmele

Mi. 16-18h, Raum RKF 009
ECDF

Topics: Quantum communication and quantum computing with atoms, ions, semiconductor quantum dots, and photons

23.10. Introductory meeting

Concepts

30.10. *Photon Antibunching in Resonance Fluorescence.* H. J. Kimble, M. Dagenais, and L. Mandel**.** *Phys. Rev. Lett.* **39**, 691 (1977)

06.11. BOS.QT Opening.

13.11. *Quantum Rabi Oscillation: A Direct Test of Field Quantization in a Cavity.* M. Brune, F. Schmidt-Kaler, A. Maali, J. Dreyer, E. Hagley, J. M. Raimond, and S. Haroche. *Phys. Rev. Lett.* **76**, 1800 (1996)

20.11. *Experimental Realization of Einstein-Podolsky-Rosen-Bohm Gedankenexperiment: A New Violation of Bell's Inequalities.* Alain Aspect, Philippe Grangier, and Gérard Roger. *Phys. Rev. Lett.* 49, 91 (1982) (T. Heindel) RFK 305

Applications

27.11. *Quantum cryptography: Public key distribution and coin tossing*, C. H. Bennett and G. Brassard, Proc. IEEE *Int. Conf. Com.* **175**, 8. (1984) (T. Heindel)

04.12. *Quantum cryptography based on Bell's theorem.* Artur K. Ekert. Phys. Rev. Lett. **67**, 661 (1991) (A. Carmele)

11.12. *Long-distance quantum communication with atomic ensembles and linear optics.* L.-M. Duan, M. D. Lukin, J. I. Cirac & P. Zoller. *Nature* **414**, 413 (2001)

18.12. *Quantum computers.* T.D. Ladd et al., *Nature* **464**, 45 (2010)

Implementations

08.01. *Quantum cryptography with a photon turnstile.* E. Waks et al., *Nature* **420**, 762 (2002) (T. Heindel)

15.1. *Observation of collective excitation of two individual atoms in the Rydberg blockade regime,* Alpha Gaëtan, et al., NATURE PHYSICS 5, 115 (2009)

22.1. *Regulated and Entangled Photons from a Single Quantum Dot.* Oliver Benson, Charles Santori, Matthew Pelton, and Yoshihisa Yamamoto*. Phys. Rev. Lett.* **84**, 2513 (2000). (A. Carmele)

29.1. Demonstration of an all-optical quantum controlled-NOT gate. J.L. O'Brien, G.J. Pryde, A.G. White, T.C. Ralph, D. Branning. *Nature* **426**, 264 (2003)

05.02. *Sudden Death of Entanglement.* Ting Yu, J. H. Eberly, *Phys. Rev. Lett.* ***93***, 140404 (2004) (A. Carmele)

30.10. *Photon Antibunching in Resonance Fluorescence.* H. J. Kimble, M. Dagenais, and L. Mandel**.** *Phys. Rev. Lett.* **39**, 691 (1977)

Presenter (10 min):
Sketch the key results on the blackboard. (Maybe use 1 Formula + 2 Figures).
Bibliometrics: what do you know about the authors and impact of the paper?
Based on the bibliometrics, do you think the paper is a milestone?

Assign titles for the different sections of the paper

Abstract:
What are photoelectric counts?
What is resonance fluorescence?
What does bunching/antibunching mean?
What is the main claim of the manuscript?
What is a quantum jump?

Introduction:
What is said about thermal light? What kind of sources emit thermal/non-thermal light?
What do you learn about the joint probability function in the classical case?
Discuss cases where this does not hold.
Glauber-Sudarshan P representation. How is Eq. (4) written in modern text books?
What is the interpretation of phi?
Translate Eq. (1) to the quantum case with creation and annihilation operators.
What says Eq (5)?

Experimental setup:
What is signal is ultimately recorded?
Why doe they use a dye laser? What is the laser wavelength?
Draw a diagram of the energy levels of sodium, incl. the relevant optical transitions
Explain the role of the optical pre-pumping beam
What is Einstein coefficient A? What does this mean in MHz?
Why are two photomultipliers involved?
How is assured that only one or two atoms contribute to the collected signal?

Results and Analysis:
What is the measured evidence for non-classical light?
How are the data corrected?
1+ lambda = g^2?
Discuss reasons for 1+ lambda != 0
Sketch Fig. 3 for beta=0; beta >> Omega
Why does lambda(tau) go down for large tau? Estimate the average transit time for the atoms.
What is a quantum jump
What is the role of non-locality in the experiment. Is there entanglement/spooky action at a distance?

Group Work (15+5 min):
Design a modern version of the experiment / formulation of the theory!

13.11. *Quantum Rabi Oscillation: A Direct Test of Field Quantization in a Cavity.* M. Brune, F. Schmidt-Kaler, A. Maali, J. Dreyer, E. Hagley, J. M. Raimond, and S. Haroche. *Phys. Rev. Lett.* **76**, 1800 (1996)

Presenter (10 min):
Sketch the key results on the blackboard. (Maybe use 1 Formula + 2 Figures).
Bibliometrics: what do you know about the authors and impact of the paper?
Based on the bibliometrics, do you think the paper is a milestone?
Take a look at C. Gerry, P. Knight “Introductory Quantum Optics,” Chapter 10.

Intro:
What are Rabi Oscillations
What is a Rydberg Atom
What is a coherent field?
What is the main claim of the manuscript?

What exactly is Planck’s hypothesis?

„However, the most generally admitted evidence of field quantization, the discrete nature of the photodetection current, is perfectly explained by a classical description of the field, provided that the linear detector is a quantum system„
How is this in line with the last paper?
Why is it so difficult to observe the discrete- ness of the energy of the radiation stored in a cavity mode?
What ist he Jaynes-Cummings Hamiltonian? Write it down.
Sketch P(n) for thermal, coherent fields and Fock states.
Sketch $P_{eg}(t)$ for various fixed n
Why ist $P_{eg}(t)$ for coherent states and Fock states with large n identical. What is with thermal fields?
What are the claim of the paper?

Setup:
Why is cooling to 0.8 K required? How can you reach such low temperatures?
What are the important properties of the atom source?
What is the mean atom transit time in the cavity?
Calculate the energy difference of n=51 and n=50 according to Bohr. Compare to the paper. Why do they speak about circular Rydberg states?
What is the wavelength?
What is the role of the electric field?
What is describes the cavity Q factor?
How does state selective field ionization work?

Why is the atom field coupling determined by the size of atom and cavity?
What is the micromaser effect?
Why is the atom cavity time essential? How is it controlled?

Results:
Why is an oscillation visible in Fig. 2A and not in 2 B-D?
Why do different frequencies show up in 2a-d?

Why does the semi-classical expectation (coherent state + Rabi oscillations) give wrong results for injected fields with average photon number ~ 1?
When are coherent states a good description for low amplitude states?

Sketch the Jaynes-Cumming ladder!
Why can the Rabi nutation be interpreted as beat signal, resulting from *coherent* excitation of superposition states.
How are vacuum Rabi oscillations detected in the frequency domain?
Which part of the experiment coupled oscillator models can explain?

Group Exercise:
Write an abstract to the paper.

20.11.2019 *Experimental Realization of Einstein-Podolsky-Rosen-Bohm Gedankenexperiment: A New Violation of Bell's Inequalities*
by Alain Aspect, Philippe Grangier, and Gérard Roger
Phys. Rev. Lett. **39**, 691 (1977)

Questions/Tasks/Stimulations:

- Bibliometrics: What do you know about the authors and impact of the paper?
- In which sense the paper is a milestone?
- Describe/Explain the EPR Gedankenexperiment and its consequences. For this purpose, discuss the Bell Inequalities and the term "hidden variables" and "local realistic theories". What is a loophole free Bell test?
- Explain the difference of classical and quantum correlations. Maybe *Dr. Bertlmann* can help you.
- Which other EPR experiments were performed before Aspect's paper and what have been their shortcomings?
- Sketch the experimental Setup used by A. Aspect et al. and explain its components including the used EPR source (energy level scheme?) and its operation principle. What are differences compared to the original EPR Gedankenexperiment?
- Summarize the execution and the results of the experiment.
- Which loopholes (cf. task 3) need to be closed to unambiguously reject local realistic theories and which of them are not accounted for in Aspect's experiment? Did other experiments close these loopholes?
- Which setup/technology would you use today to demonstrate the EPR Experiment? Provide a sketch.
- Are commercial products available for EPR epxeriments? If yes, please report their idea/concept/working principle and price .

27.11.2019 *Quantum Cryptography: Public Key Distribution and Coin Tossing* by Charles H. Bennett and Gilles Brassard *Proceedings of IEEE International Conference on Computers, Systems and Signal Processing, Bangalore, India, 175-179 (1984)*

Questions/Tasks/Stimulations:

o Bibliometrics: What do you know about the authors and impact of the paper? o In which sense the paper is a milestone? o Which problem exactly is addressed in this publication?

o Describe/Explain the “Quantum Public Key Distribution” (= BB84 protocol). Make clear: what are the essentials required for the protocol. Which of them are most challenging to realize?

o Illustrate the security of the BB84 protocol by explaining a simple eavesdropping attack (e.g. intercept-resend strategy). Which other attacks are possible? Discuss the term ‘side-channel’ in this context.

o How would you experimentally realize Alice and Bob to implement the BB84 protocol? Provide a sketch.

o Who performed the first experiment (implementation) based on the BB84 protocol? How close did this experiment follow the original idea?

o Describe/Explain the “Quantum Coin Tossing” protocol. In which way is it different/similar to the BB84 protocol and why is it important.

o Which protocol would have higher relevance in real-world applications and why? o Report about experimental implementations of “quantum coin tossing”, also

referred to as “quantum coin flipping”.

o Explain/Discuss the possibility of loopholes, i.e. “cheating”, in quantum coin tossing.

o Are commercial products for quantum communication available? Which technology are the based on? How about the price?

4.11.2019.

Ekert, *Quantum Cryptography Based On Bell's Theorem*.

Phys. Lett. Rev. 67, 661 (1991).

Questions:

- Bibliometrics. Citation Report. Development of citations in time.
- Why is the paper a milestone?
- What is the goal of the Ekert protocol?
- Compare to the BB84 protocol. What is the main difference?
- Explain the protocol in 5 steps.
- Why is the No-cloning-theorem of crucial importance? What are the conditions in the No-cloning theorem? Explain and derive the No-Cloning-Theorem.
- Are there any realizations? What is the main obstacle for a technological application?
- Is it possible to measure a quantum state without disturbing it?
- Why is the BB84 protocol more popular?
- What is the main drawback? Talk about loopholes.
- Are there other technological applications for entanglement? If so, talk about examples.
- Is the successful implementation of an Ekert protocol proof of non-locality?
- What does it mean, if Eve can eavesdrop within the Ekert protocol without having Alice and Bob having noticed it?
- Is it possible to disprove nonlocality?
- Is the notion of nonlocality important for the Ekert protocol? What is the figure of merit for a successful implementation?
- What are the requirements device independent (DVI) QKD?

11.12. *Long-distance quantum communication with atomic ensembles and linear optics.* L.-M. Duan, M. D. Lukin, J. I. Cirac & P. Zoller. *Nature* **414**, 413 (2001)

Additional literature: N. Sangouard et al., Rev. Mod. Phys. 83, 33 (2011)

Presenter (10 min):
Sketch the key results on the blackboard. (Maybe use 2 Formulas + 2).
Bibliometrics: what do you know about the authors and impact of the paper?
Based on the bibliometrics, do you think the paper is a milestone?
The presented protocol is often called DLCZ protocol. Why?

Intro
What are the main issues for long distance QKD?
What is polynomial scaling?
What is said to be the basic problem of quantum communication? Do you agree?
What is quantum teleportation?
What is the lower limit for the initial fidelity for purification of Bell states?
What is the basic idea behind a quantum repeater?
Which components are needed for a quantum repeater?

Entanglement generation
What are the experimental requirements for entanglement generation in the DLCZ protocol?
Is there an index *i* missing near s in the definition of S?
What is the state after detection of a Stokes photon? Is this state non-local?
S is called spin wave. Why? What is the wavelength?
What is the main feature of collective enhancement? Do you know a classical analogue?
What is the setup for entanglement between two atomic ensembles?
What happens when a photon is detected on D_1 or D_2?
What is the EME state?
What is the average preparation time for an EME state over distance L_0?
Why is the protocol insensitive to dark counts on D_1 and D_2 ?

Entanglement connection through swapping
What is entanglement swapping?
How is the EME state detected / converted to a traveling photon?
What is the average time deeded for generating an EME state over distance L_n

Entanglement-based communication schemes
What is the main difference between the EME state and the Bell states used in the Ekert protocol?
How can you map make the described EME states useful for QKD/teleportation?

Noise and built-in entanglement purification
How do inefficiencies influence the DLCZ protocol?
How do dark counts influence the protocol?
What happens if two excitations are generated?
Which noise contributions can/cannot be corrected in the protocol?

Scaling of the communication efficiency
Are there experimental implementations?
What are the main issues of these implementations?
What are the memory requirements for realistic scenarios?
Can you do the DLCZ protocol with single (artificial) atoms?
Why are multimode quantum memories needed?

18.12. *Quantum computers.* T.D. Ladd et al., *Nature* **464**, 45 (2010)

Presenter (10 min):
What are DiVincenzo's criteria? What are the three general criteria proposed here?
What is the key question of quantum information science?
What is the main computational resource for quantum computers (QC)?
Will quantum computers replace PCs?
Can you imagine application fields for quantum computers (QC)?
What is the difference between quantum error correction and fault-tolerance?
What are typical error thresholds for fault-tolerance?
What is the size of the logic space for a N qubit processor. What for a classical computer? Why the difference?
What means scalability?
What is needed for a universal logic?

Bibliometrics: what do you know about the authors and impact of the paper?
Do you think the paper is a milestone?

What is T_2^* in this paper? How is T_2^* defined in your community?
What is T_1 ? What T_2 ? Can you imagine experiments to measure them all? What are the underlying processes?
What does correctability imply?
Discuss the conflicts between correctability, universal logic and scalability.

Which systems for QC are discussed in the paper?
1. What is basic idea behind each of them?
2. What are the pros and cons of each of them?
3. Which components are needed?
4. Where do you see the major hurdles?
Do you know other systems that are not discussed in the paper?
Make a tabular overview for questions 2. – 4.!

Which QC approaches are investigated today (commercially and in academic context)?
What is the advantage of the commercially investigated systems?
Which system will win the race for scalable QC?

08.01.2020 with Tobias Heindel:
Quantum Cryptography with a photon turnstile
by E. Waks, K. Inoue, C. Santori, D. Fattal, J. Vuckovic, G. S. Solomon, and Y. Yamamoto *Nature (brief communications) 420, 762 (2002) + Supplementary Information*

Questions/Tasks/Stimulations:
o Provide a brief summary of the most important findings of the paper.
o Bibliometrics: What do you know about the authors and impact of the paper?
o Do you consider the paper a milestone and if so, why?
o Explain the experimental setup using a sketch. Discuss the transmission losses mentioned in the paper and how they can be improved.
o Provide details about the light source used for the experiment (cf. Refs. [6,7]).
o Which important attack is avoided or at least hindered using the presented implementation (compared to the first QKD experiment)? Explain which role g(2)(0) plays in this context and how it is exactly evaluated in the paper. Could the security (or the secure key rate) be further enhanced?
o Describe/Explain the different steps necessary to generate the final secret key in the BB84 protocol and how much each step affects the shrinkage of the key.
o The rate-loss plot in Fig. 1 is of utmost importance in the field of quantum communication. Explain the different regimes observed in this type of plot for different types of light sources (and maybe protocols). Also consider Ref [8] for this purpose.
o What are fundamental limits to the communication distance/loss in direct point- to-point QKD?

15.1. *Observation of collective excitation of two individual atoms in the Rydberg blockade regime,* Alpha Gaëtan, et al., NATURE PHYSICS 5, 115 (2009)

Presenter (10 min !):
Sketch the key results on the blackboard. Limit to 1 Eq. + 2 graphs)!
Bibliometrics: what do you know about the authors and impact of the paper?
Based on the bibliometrics, do you think the paper is a milestone?

How do Rydberg atoms interact? What is the Rydberg blockade?
Why is the Rydberg blockade so interesting?
Which potential applications are discussed? Which of them have been realized?

How do optical tweezers work?
What does a trap depth of 0.5 mK / temperature of the atoms mean?
Proof that Psi- is decoupled from the ground state, while Psi+ couples with $\sqrt{2}\ \Omega$
Why is the Rydberg state $58d_{3/2}$ chosen?
How is the excitation to the Rydberg states realized?
Why is the dipole trap turned of during excitation to the Rydberg state?
What is the upper/lower limit for the time window for excitation to the Rydberg state?
Can you observe Rydberg blockade for arbitrary strong excitation pulses?
How is the state detection realized?

What happens when two atoms are simultaneously excited to a Rydberg state?
What determines if the blockade is effective or not?
What limits the T2* time observed in Fig. 3?
What is the particularity of the collective Rabi oscillations shown in Fig. 4?

Take a look at Ref. 18! What is the key difference compared to this paper?
How can the Rydberg blockade be used to build CNOT gates?
Take a look at three follow up experiments using the Rydberg blockade. Some suggestions: Science 365, 775 (2019); *Nature* **551**, 579 (2017); Science 347, 1458 (2015); Nature 491, 87 (2012); PRL 104, 010503 (2010); https://www.atom-computing.com
Do you think this paper is a milestone?

22.1. *Regulated and Entangled Photons from a Single Quantum Dot.* Oliver Benson, Charles Santori, Matthew Pelton, and Yoshihisa Yamamoto. *Phys. Rev. Lett.* **84**, 2513 (2000). (A. Carmele)

- Bibliometrics. Citation Report. Development of citations in time.
- Why is the paper a milestone?
- What is a quantum dot? What is the difference to an atom? Why are quantum dots more attractive for device applications than atoms?
- Compare the atomic cascade with the biexciton cascade? What is the main difference?
- What determines the selection rules in a solid-state emitter?
- What enables the generation of entanglement? What is the enabling factor?
- Which processes may degrade the degree of polarization entanglement?
- Why is it necessary for the proposal to have a single quantum dot? How many atoms has a single quantum dot? How large is a quantum typically?
- Why is the Bell inequality not violated for every combination of polarisator angles?
- What is a source for spin dephasing?
- Has the energy difference between the transitions from the biexciton to exciton, and exciton to ground state any influence on the degree of entanglement?
- Can phonons degrade the degree of entanglement?
- Are there more degrees of freedom which could be entangled?
- Where does the solid-state environment enter in the discussion?
- The violation of the Bell inequality is typically not used to quantify the degree of entanglement? What are possible figure of merits?
- Which applications exist for entangled photon pairs?
- Has the proposal been realized?

29.1. Demonstration of an all-optical quantum controlled-NOT gate. J.L. O'Brien, G.J. Pryde, A.G. White, T.C. Ralph, D. Branning. *Nature* **426**, 264 (2003)

Presenter (10 min !):
Sketch the key results on the blackboard. Limit to 1 Eq. + 2 graphs)!
Bibliometrics: what do you know about the authors and impact of the paper?
Based on the bibliometrics, do you think the paper is a milestone?

What are the basic requirements for quantum computers?
What is a CNOT gate?
Write down the 4 Bell states!
What is missing to make the presented gate scalable? +

What are the advantages/disadvantages of single photon qubits?
What are the basic properties and requirements of the KLM protocol?
What are QND measurements? What is the proposed realization?

What is spatial/path enconding of qubits? What is polarization encoding?
What is the difference between classical and non-classical interference made in the paper?
Why does the control photon cause a phase shift for the target photon?
How is this phase shift converted to a bit flip? Do you se similarities to the Rydberg blockade?
What is the success probability of the gate? How is a successful operation detected?
Why is phase stability of the setup so important (and challenging)?
Can you easily map between conceptual setup and real setup?
What is a Hadamard gate?
Why is in sufficient to measure the correct gate operation for the computational basis states?
How could the non-classical interference be improved?
How is the entanglement of two qubits shown?
Why is this so important?
What do the terms "Fidelity," "Tangle," and "Linear entropy" mean?
What is quantum state tomography?
How many independent measurements are needed to reconstruct the density matrix?
How can you verify operation of a classical/quantum gate?
What is said to be the main error for gate operation? Do you believe what is said?
How could this be improved?

What are the remaining challenges for building an optical quantum computer?

5.2.2020.
Ting Yu, and J.H. Eberly, *Sudden Death of Entanglement,*
Science 323, 598 (2009).

Ting Yu, and J.H. Eberly, *Finite-Time disentanglement via spontaneous emission*, **Phys. Rev. Lett. 93, 140404 (2004).**

Questions:

- Bibliometrics. Citation Report. Development of citations in time.
- Why is the paper a milestone?
- What is the main message of the paper?
- Try to find at least three measures of entanglement? How do they differ?
- Explain the setup of the thought-experiment.
- Do you like the paper? Is it interesting? Why yes, why not?
- What is the enabling factor for the “sudden” death of entanglement (sDOE)?
- Does any decay process lead inevitably to a sDOE?
- Is it possible to measure a quantum state without disturbing it?
- What happens when the subsystem A and B are initially not entangled?
- What happens if a collective, synchronized decay takes place?
- Is the figure of merit of concurrence unambiguously defined?
- What is entanglement entropy? How is it connected to sDOE?
- Why is “entanglement” a problematic quantity of interest?
- Can the sDOE be stopped, prolonged, via quantum repeater?
- Has the sDOE been observed?
- How many discontinuous processes do you know, is sDOE one of them?
- Does sDOE always occur, is it parameter dependent, and why?
- Has the sDOE been observed?