Seminar „Milestones of Quantum Technology II"

Institute: Institut für Optik und Atomare Physik, TU Berlin
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Dates and location:
Wednesday 16-18h, Kick-off: 22.7. Last seminar: 15.7.

Online via zoom. Link to the seminar will be provided on the website.

Learning outcomes:

This module aims at reading and understanding scientific research articles. Moreover, the presentations of scientific results and the discussion of scientific topics is trained.

Teaching content:

Milestones of Quantum Technology II (summer semester)

- Parametric conversion
- Impurities in diamond
- Elements of nanophotonics
- Superconducting circuits
- Metrology

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 most of the seminars and at least one paper presentation.

Duration of the modules:
1 semester each

Milestones of Quantum Technology II

J. Wolters, S. Ramelow, T. Schröder

22.4. Kick-off.

Concepts

29.4. Indistinguishable photons from a single-photon device, C. Santori, et al., *Nature* **419**, 594 (2002)

6.5. N. H. Lindner and T. Rudolph, "Proposal for Pulsed On-Demand Sources of Photonic Cluster State Strings," Phys. Rev. Lett. **103**, 113602 (2009). (Tim)

13.5. Measurement of the quantum states of squeezed light. G. Breitenbach, S. Schiller & J. Mlynek. Nature 387, 471 (1997)

Applications

20.5. A gravitational wave observatory operating beyond the quantum shot-noise limit, The LIGO Scientific Collaboration, Nature Physics 7, 962 (2011) (Sven)

27.5. High-NOON States by Mixing Quantum and Classical Light, Itai Afek, Oron Ambar and Yaron Silberberg, Science, 328, 879 (2010) (Sven)

3.6. Quantum imaging with undetected photons, Gabriela Barreto Lemos, Victoria Borish, Garrett D. Cole, Sven Ramelow, Radek Lapkiewicz and Anton Zeilinger, Nature 512, 409 (2014) (Sven)

10.6. Experimental quantum teleportation, Dirk Bouwmeester, Jian-Wei Pan, Klaus Mattle, Manfred Eibl, Harald Weinfurter and Anton Zeilinger
Nature 390, 575 (1997) (Sven)

Implementations

17.6. One-second coherence for a single electron spin coupled to a multi-qubit nuclear-spin environment, M. H. Abobeih, J. Cramer, M. A. Bakker, N. Kalb, M. Markham, D. J. Twitchen, and T. H. Taminiau, Nature Communications **9**, 2552 (2018). (Tim)

24.6. Quantum supremacy using a programmable superconducting processor. F. Arute, et al., *Nature* **574**, 505 (2019)

1.7. Heralded entanglement between solid-state qubits separated by three metres. H. Bernien et al., *Nature* **498**, 86 (2013)

8.7. Deterministic generation of a cluster state of entangled photons, I. Schwartz, D. Cogan, E. R. Schmidgall, Y. Don, L. Gantz, O. Kenneth, N. H. Lindner, and D. Gershoni, Science **354**, 434–437 (2016). (Tim)

15.7. Network of time-multiplexed optical parametric oscillators as a coherent Ising machine. A. Marandi, Z. Wang, K. Takata, R.L. Byer and Y. Yamamoto, *Nature photon.* **8**, 937 (2013)

29.4. Indistinguishable photons from a single-photon device, C. Santori, et al., *Nature* **419**, 594 (2002)

Presenter (10 min):
Sketch the key results. (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?

What is the key difference of single photon sources (SPS) compared to Poisson-sources?
What are the most important requirements on a SPS? Why are these so important?
What is the Hong-Ou-Mandel (HOM) effect?
Can you theoretically reproduce the HOM effect on paper?
Why is the HOM so important?

Why are semiconductor quantum dots attractive for SPS?
What is the sample structure? Why is this complicated design chosen?
What is the Purcell effect?
Why is the sample cooled to 3–7 K?
How is the QD SPS excited?
What is the meaning of the $g^{(2)}$ value?
What is blinking? Can you observe the effect of blinking in Fig. 1 b?
What is the brightness of the used SPS?
What is the relation between linewidth, radiative decay rate and coherence length of an ideal SPS?
How are the spectral linewidth and the radiative decay rate measured?

What is the experimental trick to measure two-photon interference with a single photon source?
Why is a five-peak structure visible in Fig. 3 b?
What is the experimental signature of the HOM effect?
Interpret Eq. (1)!

What imperfections lead to the reduced visibilities shown in Fig. 4?
What is the relation between τ_s and τ_m? Why are the two quantities related?
Why are the HOM visibilities higher than expected from the coherence length measurement?
Which decoherence effect may influence the HOM visibility?
What is the highest HOM visibility observed in state-of-the-art experiments?

N. H. Lindner and T. Rudolph, "Proposal for Pulsed On-Demand Sources of Photonic Cluster State Strings," Phys. Rev. Lett. **103**, 113602 (2009).

Presenter (10 min):
Sketch the key results. (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?

What phenomenon does "Pulsed On-Demand Sources" refer to?
What property of the Cluster State does the "string" of "Photonic Cluster State Strings" refer to?

What is a cluster state?

Name 2 methods for the creation of entangled photonic "Bell" pairs.

What is the idea behind a fusion gate to fuse Bell pairs to cluster states?

What is the main advantage of "one-way" quantum communication and computation over original schemes regarding the efforts in measurement of the communication or computation results?

In the introduction it is stated, that "Such sources would greatly reduce the resources required to achieve linear optical quantum computation." Explain that sentence.

Why is it not sufficient to have a highly efficient source of Bell-pairs?

Is the following statement correct? Explain. "One can create 1-dimensional photonic cluster states by using a single photon source." (the answer is no :) What are the main ingredients of our stationary quantum systems ("certain single photon sources) for the generation of 1-d cluster states?

Explain briefly what a "current quantum dot sources" is.

Draw a level scheme of the quantum dot system that the authors consider.

How can a 2-level ground state (e.g. a spin-1/2 system) be brought into an equal superposition of spin-up and spin-down?

Why does an excitation laser puls polarized along the x direction couple equally to both transitions?

What is a GHZ state?

Remind yourself what a single qubit unitary is (exp(-iYpi/4)).

Follow the procedure of cluster state generation.
What is a Hadamard gate? Is it a one- or two-qubit gate?
What is a CNOT gate? Is it a one- or two-qubit gate?
What is a Pauli Y error?

What does the term ‘selection rules’ refer to here?
Draw the level structure of a heavy trion state of a quantum dot.
What are the advantages of quantum dots compared to other sources of photons?

How is the pi/2 rotation applied in the suggested protocol?
Why do certain spin states “precess”? Are they in a pure or in a superposition state?

What are the “imperfections”, hence unwanted errors occurring during the protocol?
What does the term “Pauli error” refer to here? Remember what possible errors are (bit flip, or a sign flip, both) and the Pauli matrices.

What causes decoherence of the electron spin states? What process does the term spin relaxation refer to?
Why shall the protocol not be limited by T2 times in quantum dots? What are typical T2 decoherence times of quantum dots?
What does the term “localized error” refer to?
Give an example for a (simple) single spatial mode. What are the highest coupling efficiencies from quantum dots to a single mode achieved to-date (this coupling probability is often called beta-factor)?

Illustrate how the finite ratio between trion decay and spin precession time influences the cluster state.
Under what conditions is the assumption of “instantaneous” excitation an allowed simplification?
What is a unitary operator?
Remind yourself of the simplest creation operator that you have come across in quantum mechanics.
Why does the trion state decay exponentially? What phenomenon in the cause of this?
Why can a Y error on the spin be considered the same as an Y and a Z error on the two consecutive photons?
Why is it advantageous to consider small magnetic fields? What other disadvantage do higher magnetic fields lead to considering the wavelength of the created photons?
What does the term pure dephasing refer to?
What does the term decoherence to the spin refer to?
What does the term Markovian dynamics refer to?
Try to follow the argument why finite spin decoherence times (T2) do not lead to a direct limit in the number of cluster state photons that can be generated.

Which value for a realistic error rate to the authors derive? What is the requirement? Does the consideration of high magnetic fields (several Tesla) not contradict the assumption of “only” 15 mT fields?

What is the authors idea to add further redundancy in the generation of cluster state photons. What error channels could these “tricks” help overcome?

What does one need to do to create 2-dimensional photonic cluster states?

13.5. Measurement of the quantum states of squeezed light. G. Breitenbach, S. Schiller & J. Mlynek. Nature 387, 471 (1997)

Presenter (10 min):
Sketch the key results. (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?

Why is it impossible to observe the state of a single quantum system, but possible to determine the state of an ensemble of identically prepared particles?
What is a density matrix / Wigner function?
How can a single mode light field be identified with a harmonic oscillator?
What is a quadrature component/operator? How do you measure it?
How does the photon statistics of a squeezed state look like? Can one measure it?
What kind of squeezed states do exists?

What is a balanced homodyne detector? How can it be used to measure quadratures/time evolution of a harmonic oscillator state?
How can a state be reconstructed from measured probability distributions?
Is this reconstruction unambiguous?
What are marginal of the Wigner function?

How does a degenerate parametric oscillator work?
What happens at the OPA threshold?
Why is it important to have narrow linewidth local oscillator?
How is the pump wave generated?
What are vacuum/quantum fluctuations?
What happens with the fluctuations in the OPA?
What is the role of the EOM in the setup?
Why is an OPA also called phase sensitive amplifier?
How was the measurement shown in Fig. 2 (left) taken?
How is the amount of squeezing/anti-squeezing determined?
Why are losses in detection relevant?
What is squeezed vacuum?

What is the Fock basis?
What is a super/sub-Poissonian distribution?
What is the Mandel-Q parameter?
Why does the density matrix of squeezed vacuum show a chess-board pattern?

Questions and Tips for paper: “A gravitational wave observatory operating beyond the quantum shot-noise limit”, by the LIGO Collaboration, Nature Physics volume 7, pages962–965(2011)

Sketch the key results! (Maybe use 1 Formula + 2 Figures).

Bibliometrics: What do you know about the authors (how many?) and impact of the paper? Based on the bibliometrics, do you think the paper is a milestone?

In the introduction it is stated, that “Michelson-type laser interferometers are suitable observatories to measure gravitational waves [5]”

Explain that sentence, and the importance of the reference !

In the conclusion it is stated, that “...as in contrast to increasing the laser power, increasing the squeezing factor does not increase the thermal load on the mirrors.” Explain that sentence!

What are gravitational waves and what generates gravitational waves? What frequencies are targeted by gravitational wave interferometers?

What noise sources dominate at which frequency band?

At which frequency band can quantum optics contribute to lower the noise? What is “shot noise” and how can it be reduced conventionally and why? Why is that approach limited?

How much more GWs can be detected by lowering the noise by 3dB (0.5)?

Which conjugate quantum properties can be used to describe light, how are they defined?

Which port must the squeezed light be put into the Interferometer?

How is path entanglement generated this why?

Why is it hard to squeeze light at frequencies useful for GW-detection? What was the first “practical application” of squeezed light?

What is Geo600? Why is an outmode-cleaner necessary?

How is the squeezed light generated? What kind is cavity is used? How is audio noise in the squeezing suppressed?

Why are two Faraday isolators necessary?

How much squeezing is injected?

With is the overall efficiency?

How much does it suppress the instrument noise?

How much does this improve the chances of detecting a GW? Why?

Would squeezed light also improve sensitivity at lower frequencies, if technical noise was eliminated there?

Yellow: Breakout session 1; White: Breakout session 2

High-NOON States by Mixing Quantum and Classical Light, Itai Afek, Oron Ambar and Yaron Silberberg, [Science, 328, 879 (2010)]

Presenter – 10 min:
Sketch the key results. (Maybe use 1 Formula + 2 Figures, max. 3 Slides!).
What is SPDC and how does it work.
How do the spectra of all involved light-fields look like and why?
Also: 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?

Question List Groups:

1. What is a N00N-state?
2. Why can a N00N-state be seen as a Schrödinger cat.
3. How can a N00N-state aquire a phase N-times faster, that a classical state.
4. What ist he Heisenberg-limit for phase sensing, and how is it different than the classical limit.
5. In Fig 1A – where do the states with an equal total number of photons in the state lie?
6. Setup: why are photon-number resolving detectors neccessary? How are they implemented?
7. Setup: how ist he phase-sensing interferometer implemented? What ist he advantage.
8. Which state is described be Formula (3)?
9. Which parameters have to be tuned to generate an optimal F_N?
10. Results: how long did the measurement of Fig 3G take approximately?
11. Results: whats the classical bound for 5-photon interference visibilities – and what is measured here?
12. What's the main limitation oft he setup?
13. How is the present approach similar to squeezed light phase-sensing?
14. Why is loss such a fundamental problem for scaling this N00N-state approach to very large photon numbers?

Question-List for “Quantum imaging with undetected photons”,
doi:10.1038/nature13586

Presenter – 10 min:
Sketch the key results. (Maybe use 1 Formula + 2 Figures, max. 3 Slides!).
What property of SPDC is used to enable wide-field imaging.
Also: 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?

Question List Groups:

1. What is so special/strange about „induced coherence without induced emmision“?

2. What ist he key difference to „ghost imaging“?

3. Who invented the special „induced coherence without induced emmision“-interferometer?
(hint: look at the footnotes in Ref. 3)

4. How can absorption in path d be detected looking only ant g/h? How can a phase-shift in path d be detected looking only at g/h?

5. How many photons interfere at BS2?

6. In which step in the derivation of formular (1) is the indististiguishablity between the two idler modes used?

7. What ist he (physical) origin oft he sharp spatial correlations betwen signal and idler light used here?

8. Setup: What are the different planes indicated in Fig. 2?

9. How does the lens system work und could it theoretically be done differently as well?

10. Why could the non-degenerate wavelengths be useful?

11. How does phase imaging an at 800nm invisible object with an 800 nm Camera work?

12. What would happen if the pump laser would be replaced with a single photon source.

13. What ist he maximal visibility in a single arm for intensity- and phase imaging?

14. For both phase- and absorbtion imaging: For N detected photons on the camera – how many partner idler photons interacted with the object ?

15. What is the significance of Extended Data Figure 2?

16. What is meant be the last sentence oft he main text?

Question-List “Experimental Quantum Teleportation”, Nature 390, 575 (1997)

Presenter – 10 min:
Sketch the key results. (Maybe use 1 Formula + 2 Figures, max. 3 Slides!).

Also: 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?

Question List Groups:

1. Why can one not measure a quantum state and then send the information classically and then reconstruct it?
2. Who called entanglement “THE essential feature of quantum mechanics “?
3. How many particles could be entangled experimentally prior to the paper?
4. What reasons could Alice have to not send her state directly to Bob?
5. Which photon degree-of-freedom is used here? Which other degree-of-freedom could also be used?
6. Which quantum postulate is used in the teleportation protocol? What does it mean?
7. What main ingredients as needed in the teleportation protocol? How many photons are necessary.
8. How many photons are used in the experiment, and what is the role of photon 4?
9. What is “spooky action at a distance”?
10. How many Bell-states are there, how many are detected by the experiment, how?
11. What is the no-cloning theorem and how is it circumvented by teleportation?
12. How is polarization entanglement produced in the experiment?
13. What is special about the phi- state?
14. For which states was teleportation demonstrated, and why is this sufficient?
15. What are “spurious coincidences” and where do they come from?
16. Estimate the measurement time for the data in fig. 4!
17. What happens when you teleport the state of a photon that is already entangled to another photon?

Questions - M. H. Abobeih et al, "One-second coherence for a single electron spin coupled to a multi-qubit nuclear-spin environment," Nature Communications **9**, 2552 (2018).

What is the highest (at time of publication) measured electron spin qubit coherence time in *any* material system? Differentiate between a single electron spin and an ensemble.

What was the "trick" until this paper to achieve record coherence times for electron qubits?

Why are electron spins that experience this "trick" not relevant for future quantum registers?

How many individual nuclear spins do the authors consider in this work? How many spins in total?

How can the coupling strength between the nuclear spin reveal the distance and the angle to the magnetic field?

The natural abundance of 13C is 1.1%. What makes up the rest of the diamond?

How does the single-shot spin state read-out work?

How do we call the longitudinal relaxation (T1) in the optical domain?

How many hours will the electron spin stay in any prepared initial state?

What is the limit for the measured T1 time?

What is the most simple "dynamical decoupling" scheme? Explain briefly using a group of sprinters on a race track.

Why do the dips in Fig. 2a represent an interaction with the nuclear-spin environment?

Considering first the 7 individual spins:

What is "hyperfine coupling"? Between what particles specifically is this phenomenon observed here? How does this turn into decoherence?

How can the electron spin be decoupled from coupling to nuclear spins that is based on hyperfine coupling? What is the Larmor frequency? (See Ref. [33])

Considering the 6 spin pairs: What does the term strong coupling refer too? How close are the 2 nuclear spins per pair? How can a pair of strongly coupled spins be modeled to simplify their theoretical treatment?

The coupling of these spin pairs to the electron spin depends on the electron spin state. Why?

In Fig. 3: How does a spin Ramsey measurement work? Explain the quantum circuit diagram in a. Why are the precession frequencies generally higher for the electron spin being in m_s=1? Why are they unchanged for Pair 4 in b and c?

In Fig. 4: Set the relative position of the nuclear spin pairs in relation to the measured coupling frequencies.

In Fig. 5: Why could Fig. a be misleading? Check Suppl. Fig. 7. Also Fig. 5 c can be better understood together with Suppl. Fig. 7.

Taking a look at Suppl. Fig. 8, why is the fact that m_s=0 and m_s=1 states scale similar to the superposition states indicates that the fidelities are likely limited by pulse errors?

Summarize the most exciting outcome and perspective of this work.

Quantum supremacy using a programmable superconducting processor. F. Arute, et al., *Nature* **574**, 505 (2019)

Presenter – 10 min:
Sketch the key results. (Maybe use 1 Formula + 2 Figures, max. 3 Slides!).

Also: 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?

1. What is essential for the advantage of quantum computers?
2. What is quantum supremacy and what are the key challenges for reaching it?
3. What exactly has been demonstrated in this paper?
4. Which computational task is solved?
5. How is the operation of the quantum processor verified? Is thin in contradiction to the claimed quantum supremacy?
6. What is the "linear cross-entropy benchmarking fidelity"?
7. What is a transmon qubit?
8. What is the Sycamore processor architecture?
9. Which gates are implemented on the processor?
10. What is the needed "experimental overhead" to run the processor?
11. Can you explain the measurements shown in Fig. 2?
12. What is the total fidelity for the largest investigated circuits?
13. What is the finally computed algorithm?
14. Does the paper show any result from a measurement where quantum supremacy is visible?
15. Which computers were used for simulating the quantum circuit? Can one improve the computational methods to efficiently verify google's samplings?
16. What is the digital error model?
17. Is it straightforward to realize a universal quantum computer by building on google's results? How fast will computational power of quantum processors grow in future?

1.7. Heralded entanglement between solid-state qubits separated by three metres. H. Bernien et al., *Nature* **498**, 86 (2013)

Presenter: Sketch the used entanglement protocol and the key results (max. 3 Slides!).

Also: 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?

1. What is entanglement and what is it useful for? How can entanglement be experimentally measured?
2. What is the atomic structure of the NV^- center in diamond? What is NV^0?
3. Can you sketch the relevant level structure and possible transitions of the NV^- center in diamond?
4. How does the NV fluorescence spectrum look like? What is a "zero phonon line" and a "phonon side band"?
5. What do the authors mean by "single shot read out"? Why is this important?
6. How does the used entanglement protocol work? Can you explain all key steps?
7. Why are two photon detection events necessary to herald entanglement?
8. Why is the photon indistinguishability relevant?
9. What are spectral jumps and how is the effect of jumps mitigated?
10. What is a solid immersion lens? Why is it used here?
11. How is the HOM experiment measured as a side result from the entanglement experiment?
12. Which specific measurements are taken to proof entanglement?
13. Do the experimental data violate a Bell-type inequality? Do they show entanglement?
14. What is the success probability of the entanglement protocol? At which rate is entanglement generated?