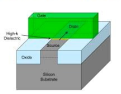
Quantum electrodynamics and quantum optics

Fall 2024

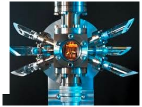
Quantum Science

- Quantum theory has affected every day of our lives: atomic clocks for GPS, transistors, optical comm.

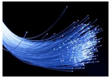
$$H(t)\,|\,\psi(t)\rangle = i\hbar \frac{d}{dt}\,|\,\psi(t)\rangle$$



transistors

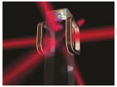


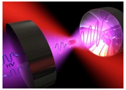
atomic clocks

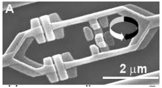


Photoelectric effect

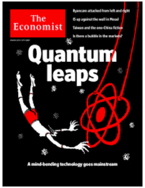
- Manipulation of quantum systems is unprecedented: **atoms, ions, molecules, superconducting circuits, solid state systems to macroscopic systems…**

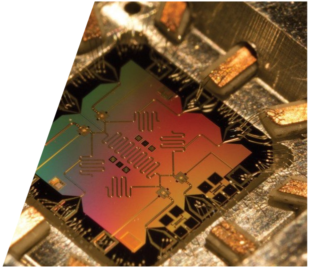




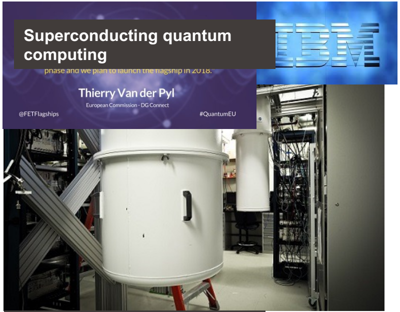


  - Quantum computation
  - Quantum network/communication
  - Quantum simulation
  - Quantum metrology





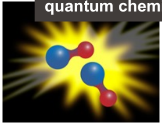
QST potential across disciplines



Superconducting quantum computing

Superconducting detectors offer high-speed astronomy

Ultracold molecules for quantum chemistry

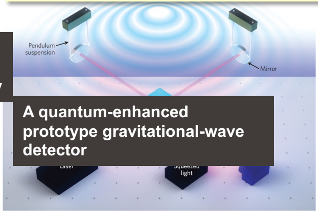


Very active research fields

- Largescale efforts (e.g. EU Flagship on Quantum)
- Large Quantum Progams at leading institutions (ETHZ, Kavli Delft,
- Nobel Prizes: BEC, Laser Cooling, Quantum Control,...

Quantum across disciplines

- Astronomy
- Gravitational wave detectors
- Biology
- Chemistry



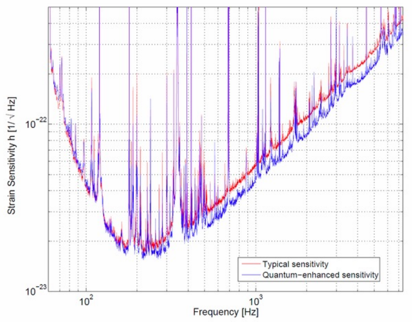
A quantum-enhanced prototype gravitational-wave detector

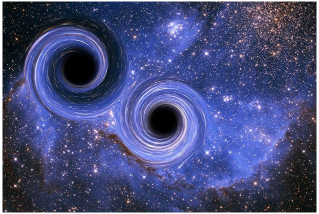
Quantum Science for Precision Measurements

NEWS · 15 FEBRUARY 2019

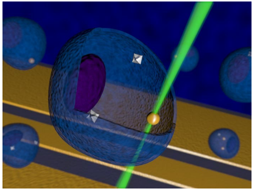
Gravitational-wave observatory LIGO set to double its detecting power

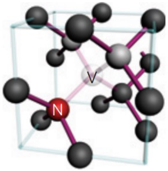
A planned US$35-million upgrade could enable LIGO to spot one black-hole merger per hour by the mid-2020s.

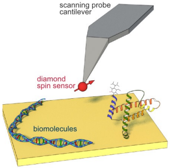




QST potential across disciplines

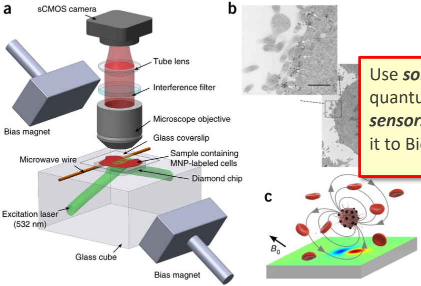






- Electric-field sensing using single diamond spins *Nature Physics*

Use ***solid quantum systems*** (e.g. defects in NV) and quantum optics methods to creates ***nanoscale sensors*** for Voltage, Charge, Temperature and apply it to Biology or nanoscale NMR.

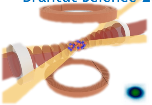


- Single-cell magnetic imaging using a quantum diamond microscope, *Nature Methods*

Experimental Research in QST at EPFL

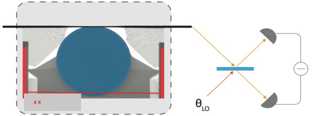
Ultracold atoms Quantum Simulations (Brantut)

- Roux Nature Comm. 2020
- Brantut Nature, 2015
- Brantut Science 2013



Quantum measurements (TJK)

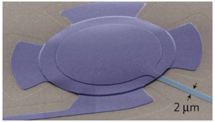
- Wilson, Nature, 2015
- Aspelmeyer Rev. Mod. Phys. 2015



$$\frac{d\hat{\rho}}{dt} = -\frac{i}{\hbar}[\hat{H}, \hat{\rho}] + \mathcal{L}(\hat{\rho})$$

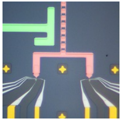
Superconducting quantum optomechanics and qubits

- Youssefi et al. Nature (2022)



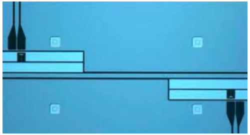
Hybrid Quantum Systems (Scarlino)

- Stockklauser, Scarlino, PRX 2017



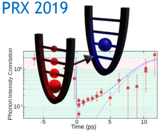
Superconductor Quantum Information (Manucharyan)

Mehta al. Nature (2023)



Molecular quantum optomechanics (Galland)

- S. Tarrago-Velez, Galland PRX 2019



Course topics

- Quantization of the electromagnetic field
  - Week 1: Quantization of a Harmonic Oscillator, quantization of electrical circuits, field quantization
  - Week 2-3: Fock states, coherent states and squeezed states
- Measuring the quantum States of Light
  - Week 4: Phase space representations (Q-function, Wigner function, P-representation)
  - Week 5: Homodyne detection
  - Measurements, photon counting
  - Photon correlations, HBT effect, g(2) measurements
- Superconducting circuits
  - Week 6: Josephson Junctions
  - Copper pair box and Transmon
  - Circuit quantization

Course topics

- Atom field interaction
  - Week 7-8: Light matter interaction, dipole approximation, atom-field interaction Hamiltonian
  - Week 9: Quantum optics of an open cavity, Purcell effect
  - Week 10: Cavity quantum electrodynamics (cQED): strong coupling, dispersive regime
  - Applications of cQED: Generation of arbitrary quantum state of a harmonic oscillator, Quantum Metrology, QND measurements of TLS
- Introduction to quantum mesaurements
  - Week 11: Quantum non-demolition measurements
  - Quantum backaction in linear measurements
  - Week 12: Quantum limits of interferometric measurements
  - Week 13: Pondermotive Squeezing
  - Week 14: Backaction-Evading Measurements
  - Quantum theory of an amplifier

Course rules

- The course will be held in hybrid mode. In person lectures will be held and streamed via zoom.
- **Written exam at the end of the semester**. The content will be communicated towards the end of the semester.
- Homework is due by the beginning of the next week's exercise session, late submissions will not be graded. **Only the starred exercises are graded**.
- The exercise session will be held in person in Q&A format.
- Handwritten notes are uploaded to Moodle for reference only. We welcome mistake spotting (feedback to TAs).

Course Structure

- A video lecture will be uploaded to Moodle each week for self learning. In some parts the video quality might not be very good, we apologize for the inconvenience.
- Each week a student will present a paper. The presentation should be around 40 minutes long. Presenters should follow the Beamer template on course Moodle. The slides should be shared with the TAs at least one day before the course.
- Sign up for a presentation/question slot shortly after this lecture (google doc link on Moodle). 13 Topics in total. Send an email to evgenii.guzovskii@epfl.ch
- In week $(n+1)$'s classroom, first a 30 min summary will be given of week n's lecture video, then the one student will present the paper for one hour.
- Students should both watch the videos and read the paper of week n before next thursday's course.

Grading Policy

Depending on whether you submit homeworks and/or make a presentation, the weight of the final exam towards the final grade might be different:

- Option 1: 100% - exam
- Option 2: 90% - exam, 10% - homework/presentation
- Option 3: 80% - exam, 10% - homework, 10% - presentation

Your final grade will be the maximum between these three options
The assessment of the presentation is binary. The assessment of the homeworks is also binary with an 80% threshold.

Course Comments

- Although this course requires far more than 6 credits of work, which is not a big deal for me, I find that we are left alone and I feel that the teacher does not give any lessons just some summary of the books we have to read and the videos of the course he gave last year, it is a little bit frustrating to have to watch some zoom videos instead of real teaching. Another thing is that we have not access to any corrections to the exercicses just some feedbacks from the assistant teachers and I believe it is very difficult to improve our skills and learn from our errors wihout a thorough corrected version of the exercises.
- Difficult, but I have better understanding after hours with homework. I feel the course like 8 credit, rather than 6.
- I don't mind graded exercises but not giving a correction is a terrible idea in my opinion. Learning usually happens by making mistakes and correcting them, but with the current system it's hard to know if we even made a mistake in the first place. A grade and a small comment don't give much information. It's especially hard for those who can't go to the exercises sessions. Other than that the content is interesting.
- I like this format in general, but I'm not convinced by the organisation of the exercise session. An assistant show us a way to solve the exercises, but not necessarily the one that we followed, so we cannot know during the exercise session if we're right except if we ask directly an assistant, but there is not necessarily enough time for everybody to do that. Moreover, this course takes a lot of time (which is not a problem in itself) but often I come to the exercise session for nothing because I understood everything correctly so I loose 2 additional hours that I could have used for something else. I think that it would be useful to solve both of this problems for example by fixing the deadline on Wednesday afternoon and giving just the final results shortly after that, so that one can guess if it is useful for them to go to the exercise session on Thursday morning. Another possibility that I can think of would be to change the exercise session into a session during which everybody could ask their questions about the correction given for the precedent week. Also it could be useful to use a forum so that students can easily ask general questions about the exercises, not about how to solve them obviously, but to understand more clearly what we are supposed to do. For example on some exercise session we were asked to compute the time evolution of a coherent state, but it was written in the exercise sheet that the wave function at time t=0 was some psi_0 defined as the ground state, which is by definition a state that doesn't evolve in time. Therefore I couldn't follow the direction we were given. It was not a problem since I solved it another way but maybe it was confusing for other student. Finally I like the fact that by reading papers each week we have concrete ideas of how the knowledge acquire is used in modern experiment, but it takes a lot of time to read them carefully and the exercises already take a lot of time. Honestly I often read them quickly and then just listen to the presentation on Thursday. Perhaps we could instead directly do lectures every thursday on modern applications. I have criticized a lot of things, but don't get me wrong, as I said above I already like this way of learning, I just wanted to gives some ideas on what could be changed.
- Inverted classroom is the worse scam, of course student learn better, it doubles their workload. A teacher can only do it because the other teacher’s don’t, if everybody started doing it it would be untenable. And if we already have to watch videos, it would be appreciated if they were of good quality (good sound and with a readable blackboard). It’s a shame because the material is really interesting. The summary slides are really appreciated.
- Not particularly fond of the asynchronous teaching style or the "figure it out yourself" approach to exercises. Would prefer a more traditional teaching style for a subject this complex
- The class is very interesting, but a lot of work, even for six credits. As an engineer the lectures are difficult to follow, because we haven't really seen any of the operations used (e.g. the bra-kez notation). It would maybe be helpful to have some sort of cheat sheet that explains some of the basics, that we should know before the class starts. The course lists "Quantum Physics" as a prerequisite, but it should maybe be specified, that it should have been a quantum physics class for physicists and not for engineers. It's difficult to solve the exercises without being able to ask questions while doing them, especially for the comprehesion of the exercise itself.
- The course appears well developed, and the teacher and TA's are good. However, I find the amount of homework, and work in general, to be unfair as reflected by the credits and prerequisites. It easily takes 15-20 hours per week if one wants to actually understand the subject matter, all while doing the exercises and trying to read the week's articles.
- The course is developing very well the themes of quantum electrodynamics and quantum optics. However, the number of credits are not proportional to the workload. Indeed, we get videos of class to watch ourselves in complement of the class. The exercises set are really really long.
- the discussion about the article from 10 to 12 is difficult to follow for me, as I don't understand well (I don't have lot's of time during the week to study in details the article(s)).
- The weekly video lectures are hard to follow because of sound quality and it is sometimes hard to read the blackboard.
- Though I find the lecture interesting, I think it fails to give a solid and clear basis in quantum optics and QED. I think we should take more time to go over the basics before going into modern research. For some reason, I feel like the lecturer assumes every student has a profound understanding and extensive knowledge of experimental quantum optics. I believe I lack the language and tools to get a grasp of the papers we are reading after doing a Bachelor which mostly focuses on theory. I see the point that Prof. Kippenberg makes about being aware of more modern developments of the field but I don't think I am equipped after a few lectures to learn about them. About the videos : they are difficult to follow, especially the figures on the board are often impossible to read, there are many mistakes, etc. This could be maybe be improved by writing them on some kind of iPad... The homework is usually helpful to understand the subject and challenging in a good way. I also like that we can receive a bonus for them. However some tutors could explain a bit better the solution, more into details, etc.
- Tremendously interesting but extremely demanding course, probably closer to 8 credits rather than 6. While I agree that the time is well spent and that the teaching method actually produces high quality learning, I feel that the audio quality of the recorded lectures is too low and I sometimes feel like I don't learn much from them. They don't feel as impactful as they should be. Recording them properly would help a lot in guiding through the helpful, but very voluminous reference material; I agree with Prof. Kippenberg's argument about superstar lecturers giving a false sense of security, but I nonetheless think that the lectures should be a guiding light in the sea of references. Context switching between 5+ different books is not the easiest task. The homeworks also sometimes aren't as useful as they could be. The TAs seem to notice the problems and listen to our feedback, so it would probably help to adjust the questions a bit based on their findings. Overall, the selection of exercises is well made but could still be improved by slightly modifying some of them.
- Very interesting course, filled with a lot of super interesting content and learning a lot. A lot of work, so only for interested people, the active learning is interesting but maybe would be nice to do once every two weeks a full q&a session on the course as I often have questions on the material, and the videos are quite fast paced, quality of audio and video is not good enough some times Also would be nice to have a mock exam or some info on the shape the exam will take,
- Very interesting, but 6 credits are not nearly enough for the work expected. Inversed classroom is a nice idea, but here I feel it is more like an added classroom, because of the paper presentations, which are demanding to follow aswell. Having a paper presentation only every second week could help. Also a solution sheet for the exercices would help me more, than seeing the assistant solving the exercises once during the exercice sessions. But overall an extremely interesting course and I like that scientific papers are an important part of the lectures.

Course Comments

- Active learning does require everyone's participation.
- The course recordings are at times not perfect. We are working on re-making the audio.
- This course is a lot of work (more than the credits suggest)
- Handwritten notes are not always well legible - but note, they are not replacing the actual primary sources that are referenced.
- Now most of the homework solutions will be uploaded to moodle.

Teaching Philosophy: post COVID

- From: https://www.science.org/doi/epdf/10.1126/science.abj9957

Teaching philosophy

EDUCATION

Active learning: “Hands-on” meets “minds-on”

Widespread disruptions to schooling spurred by COVID-19 have amplified long-standing discussions about what high-quality teaching and learning can be. Growing bodies of research and practice, from early childhood to university classrooms and beyond, demonstrate the benefits of moving beyond traditional lecture-driven approaches in favor of “active learning.” Such approaches put students more in the driver’s seat through discussions, in-class questions, and feedback; interactive technologies; and other strategies to engage learners and deepen understanding. Beyond cognitive and academic benefits, active-learning approaches can also provide socioemotional support, particularly for students who may not feel at home in or supported by traditional passive learning. But there is no single active-learning approach. Instead, as the experts below describe, we see a rich and developing portfolio of methods and ideas supporting different ways to produce more effective learning. **—Brad Wible**

Students may learn more than they think

By **Louis Deslauriers[8], Logan McCarty[8,9], Kristina Callaghan[8,10]**

Despite strong evidence that active learning based on the principles of deliberate practice produces better educational outcomes (*17*), traditional lecturing remains the dominant mode of instruction in college STEM courses (*18*). Why are students and faculty slow to embrace active learning, which seeks to cognitively engage students and to promote peer interactions? In large part, the effortlessness associated with listening to a well-presented lecture can mislead students (and instructors) into thinking that they are learning a lot.

We compared students' perception of learning with their actual learning in college physics classrooms (*19*). During one class session, half the students were randomly assigned to a class that used active learning (experimental treatment) consisting of students working in small groups on carefully designed in-class activities, followed by instructor feedback tailored to student comments and questions during group work. The other half of the students attended a well-presented lecture (control treatment). The roles were reversed in the subsequent class session. Both experimental and control groups used identical course materials and only the students' active engagement with the material was toggled on and off. We repeated the same experiment twice in different courses, and the results were the same: Students learned significantly more with active learning (as expected), and they also felt that they learned from it—but their feeling of learning was more pronounced with the well-presented traditional lectures.

These misperceptions have broad implications for STEM education. Course evaluations based on students' perceptions of learning could inadvertently promote inferior methods of instruction—a superstar lecturer can explain things in such a way as to make students feel like they are learning more than they actually are. By contrast, the cognitive effort involved in active learning is a sign of effective learning, even if students may not always perceive it that way. Moreover, these perceptions of learning may also play a role with popular active-learning methods that rely heavily on instructor feedback (*17*, *20*). We recommend that instructors intervene early in the semester to discuss notions of learning versus the feeling of learning and persuade students that they are in fact benefiting from the sustained mental efforts associated with active learning (*19*). This mismatch between actual learning and the feeling of learning must be addressed and understood by faculty and students for these proven instructional strategies to be more effective and to become widespread.

guidance which certainly belongs after the lecture on rotating systems, but which was, unfortunately, omitted. The fifth and sixth lectures are actually due to Matthew Sands, as I was out of town.

The question, of course, is how well this experiment has succeeded. My own point of view—which, however, does not seem to be shared by most of the people who worked with the students—is pessimistic. I don't think I did very well by the students. When I look at the way the majority of the students handled the problems on the examinations, I think that the system is a failure. Of course, my friends point out to me that there were one or two dozen students who—very surprisingly—understood almost everything in all of the lectures, and who were quite active in working with the material and worrying about the many points in an excited and interested way. These people have now, I believe, a first-rate background in physics—and they are, after all, the ones I was trying to get at. But then, "The power of instruction is seldom of much efficacy except in those happy dispositions where it is almost superfluous." (Gibbons)

Still, I didn't want to leave any student completely behind, as perhaps I did. I think one way we could help the students more would be by putting more hard work into developing a set of problems which would elucidate some of the ideas in the lectures. Problems give a good opportunity to fill out the material of the lectures and make more realistic, more complete, and more settled in the mind the ideas that have been exposed.

I think, however, that there isn't any solution to this problem of education other than to realize that the best teaching can be done only when there is a direct individual relationship between a student and a good teacher—a situation in which the student discusses the ideas, thinks about the things, and talks about the things. It's impossible to learn very much by simply sitting in a lecture, or even by simply doing problems that are assigned. But in our modern times we have so many students to teach that we have to try to find some substitute for the ideal. Perhaps my lectures can make some contribution. Perhaps in some small place where there are individual teachers and students, they may get some inspiration or some ideas from the lectures. Perhaps they will have fun thinking them through—or going on to develop some of the ideas further.

RICHARD P. FEYNMAN

June, 1963

Quantum Electrodynamics (QED) effects

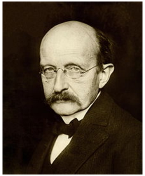
Quantum Electrodynamics (QED) effects

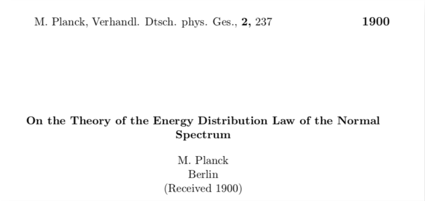
The existence of zero point energy of size $\hbar\omega/2$ is possible.

——— Albert Einstein 1913

Quantum Electrodynamics (QED) effects

1900 Planck discovered that spectral distribution of thermal light can be derived from postulating energy of an harmonic oscillator to be quantized.



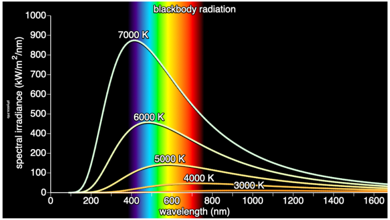


M. Planck, Verhandl. Dtsch. phys. Ges., **2,** 237 **1900**

On the Theory of the Energy Distribution Law of the Normal Spectrum

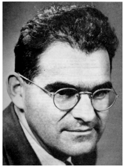
M. Planck
Berlin
(Received 1900)

$$B_\nu(\nu, T) = \frac{2h\nu^3}{c^2}\frac{1}{e^{h\nu/kT} - 1}$$



Quantum Electrodynamics (QED) effects

1930 The theory of the spontaneous emission under the QED framework was first calculated by Weisskopf and Wigner.



Berechnung der natürlichen Linienbreite auf Grund der Diracschen Lichttheorie*.

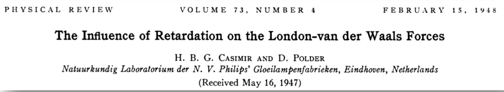
Von **V. Weisskopf** in Göttingen und **E. Wigner** in Berlin.

Mit 3 Abbildungen. (Eingegangen am 2. Mai 1930.)

Es werden die Diracschen Gleichungen der Wechselwirkung zwischen Atom und Strahlung in einer von der üblichen verschiedenen Art näherungsweise gelöst. Die Lösungen gelten während der ganzen Zeit, die für die Emission praktisch in Betracht kommt, mit der gleichen Näherung und liefern den Intensitätsverlauf in den Emissionslinien des Atoms.

Quantum Electrodynamics (QED) effects

1948 The Casimir effect was first predicted in 1948 by Hendrik Casimir of Philips Research Laboratories in the Netherlands.



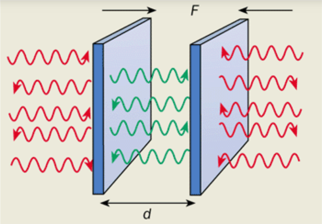
PHYSICAL REVIEW VOLUME 73, NUMBER 4 FEBRUARY 15, 1948

The Influence of Retardation on the London-van der Waals Forces

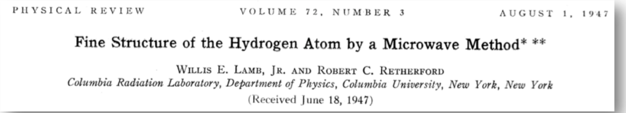
H. B. G. Casimir and D. Polder

Natuurkundig Laboratorium der N. V. Philips' Gloeilampenfabrieken, Eindhoven, Netherlands

(Received May 16, 1947)

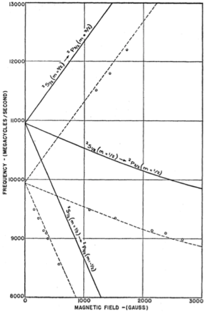


Quantum Electrodynamics (QED) effects

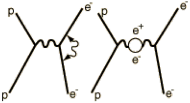

PHYSICAL REVIEW VOLUME 72, NUMBER 3 AUGUST 1, 1947

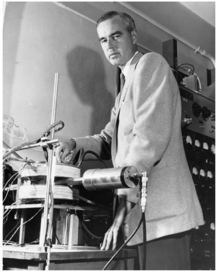
Fine Structure of the Hydrogen Atom by a Microwave Method* **

WILLIS E. LAMB, JR. AND ROBERT C. RETHERFORD
Columbia Radiation Laboratory, Department of Physics, Columbia University, New York, New York
(Received June 18, 1947)



1947 The Lamb shift was first measured in 1947 in the Lamb–Retherford experiment on the hydrogen microwave spectrum and this measurement provided the stimulus for renormalization theory to handle the divergences..

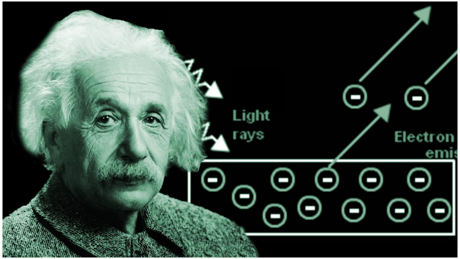




Historical Development of Quantum Optics

Historical Development of Quantum Optics

1905 Photoelectric effect could be explained by quantized energy states of light.

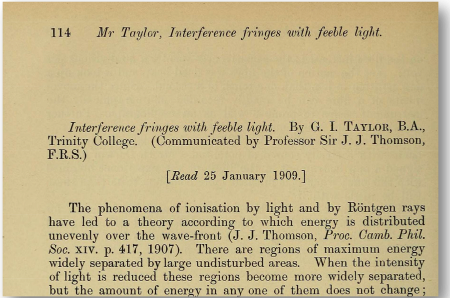


6. *Über einen die Erzeugung und Verwandlung des Lichtes betreffenden heuristischen Gesichtspunkt;*
von A. Einstein.

Zwischen den theoretischen Vorstellungen, welche sich die Physiker über die Gase und andere ponderable Körper gebildet haben, und der Maxwellschen Theorie der elektromagnetischen Prozesse im sogenannten leeren Raume besteht ein tiefgreifender formaler Unterschied. Während wir uns nämlich den Zustand eines Körpers durch die Lagen und Geschwindigkeiten einer zwar sehr großen, jedoch endlichen Anzahl von Atomen und Elektronen für vollkommen bestimmt ansehen, bedienen wir uns zur Bestimmung des elektromagne-

Historical Development of Quantum Optics

1909 G.I. Talyor attempted to find quantum effects of light via optical interference using single photons.



114 *Mr Taylor, Interference fringes with feeble light.*

Interference fringes with feeble light. By G. I. Taylor, B.A., Trinity College. (Communicated by Professor Sir J. J. Thomson, F.R.S.)

[*Read* 25 January 1909.]

The phenomena of ionisation by light and by Röntgen rays have led to a theory according to which energy is distributed unevenly over the wave-front (J. J. Thomson, *Proc. Camb. Phil. Soc.* xiv. p. 417, 1907). There are regions of maximum energy widely separated by large undisturbed areas. When the intensity of light is reduced these regions become more widely separated, but the amount of energy in any one of them does not change;

Historical Development of Quantum Optics

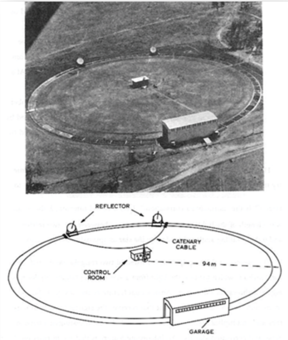


Figure 1. Aerial photo and illustration of the original HBT apparatus. They have been extracted from Ref.[1].

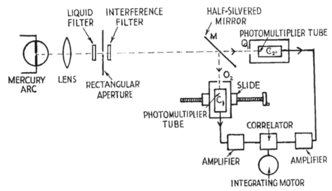


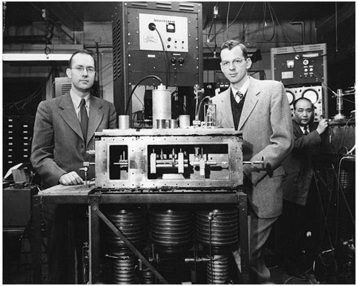
Fig. 2. Simplified diagram of the apparatus

1954 Hanbury-Brown-Twiss experiment realized the measurement of two-time intensity autocorrelation functions which gives photon bunching.

Historical Development of Quantum Optics

1954 Working with Herbert J. Zeiger and graduate student James P. Gordon, Townes demonstrates the first maser at Columbia University.

1960 Theodore H. Maiman, a physicist at Hughes Research Laboratories in Malibu, Calif., constructs the first laser using a cylinder of synthetic ruby measuring 1 cm in diameter and 2 cm long, with the ends silver-coated to make them reflective and able to serve as a Fabry-Perot resonator. Maiman uses photographic flashlamps as the laser's pump source.

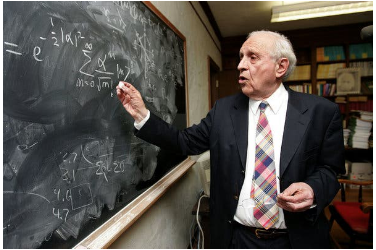


Historical Development of Quantum Optics

PHYSICAL REVIEW VOLUME 130, NUMBER 6 15 JUNE 1963

The Quantum Theory of Optical Coherence*

ROY J. GLAUBER
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts
(Received 11 February 1963)



1963 Glauber's quantum theory of coherence predicted anti-bunching of light (classical theory would require negative probabilities)

Historical Development of Quantum Optics

1975-1976 Prediction and measurement of non-classical light in two level systems (resonance fluorescence) → Quantum Optics

A quantum-mechanical master equation treatment of the dynamical Stark effect

H J Carmichael† and D F Walls
School of Science, University of Waikato, Hamilton, New Zealand

Received 7 November 1975, in final form 28 January 1976

Photon Antibunching in Resonance Fluorescence

H. J. Kimble,[a] M. Dagenais, and L. Mandel
Department of Physics and Astronomy, University of Rochester, Rochester, New York 14627
(Received 22 July 1977)

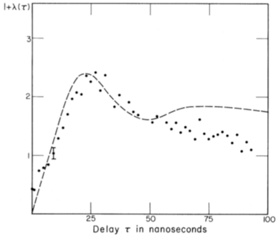
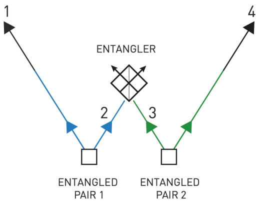


FIG. 3. Values of $1+\lambda(\tau)$ derived from the data. The broken curve shows the theoretically expected form of $\langle \hat{I}_G(\tau)\rangle$ (with $\Omega/\beta = 4$) for a single atom, arbitrarily normalized to the same peak.

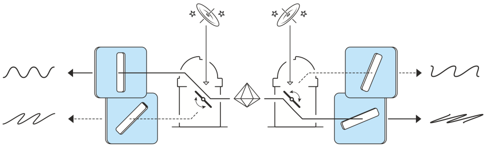
Modern Developments of Quantum Optics

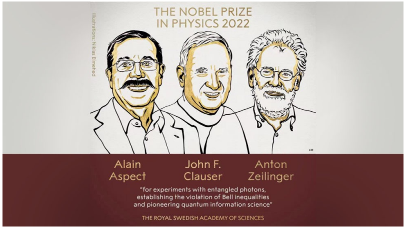
Quantum Entanglement

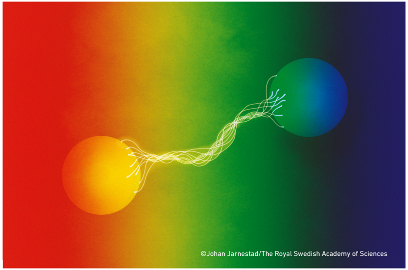
Entangled Photons



Bell Test







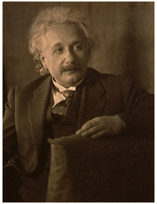
EPR paradox

MAY 15, 1935 PHYSICAL REVIEW VOLUME 47

Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?

A. Einstein, B. Podolsky and N. Rosen, *Institute for Advanced Study, Princeton, New Jersey*

(Received March 25, 1935)



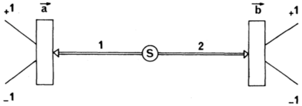
Volume 49, Number 2 PHYSICAL REVIEW LETTERS 12 July 1982

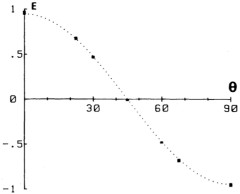
Experimental Realization of Einstein-Podolsky-Rosen-Bohm *Gedankenexperiment*: A New Violation of Bell's Inequalities

Alain Aspect, Philippe Grangier, and Gérard Roger

Institut d'Optique Théorique et Appliquée, Laboratoire associé au Centre National de la Recherche Scientifique, Université Paris-Sud, F-91406 Orsay, France

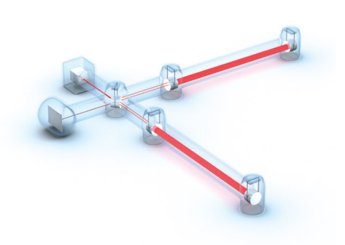
(Received 30 December 1981)

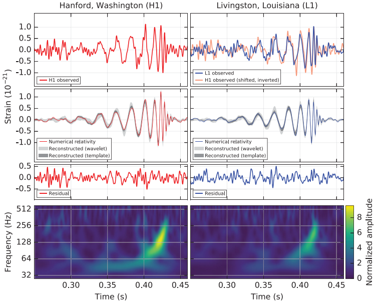




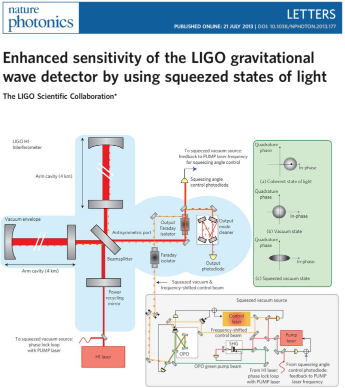
Gravitational wave detection

Quantum and thermal noises in gravitational wave detectors



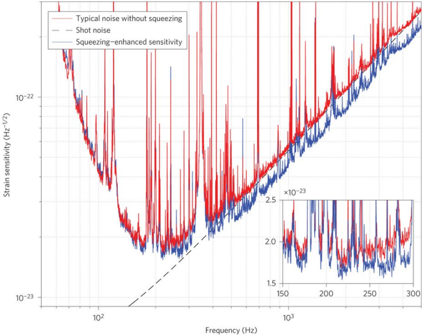


Gravitational wave detection

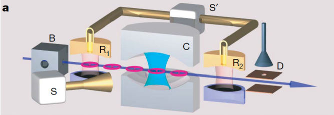

nature photonics
LETTERS
PUBLISHED ONLINE: 21 JULY 2013 | DOI: 10.1038/NPHOTON.2013.177

Enhanced sensitivity of the LIGO gravitational wave detector by using squeezed states of light

The LIGO Scientific Collaboration*



Cavity quantum electrodynamics



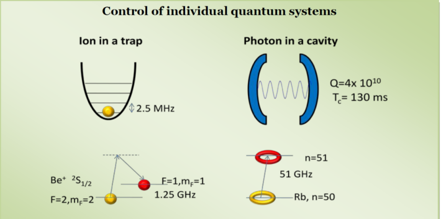
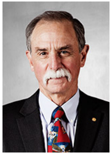


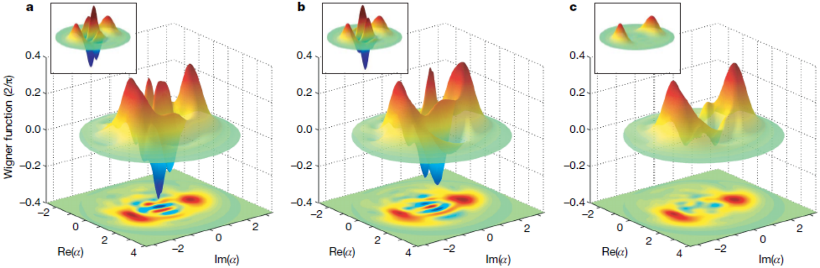
Fig. 1: Illustration of the two types of experiments discussed in this scientific background: On the left, an ion is captured in a harmonic trap. Its quantum state (both its internal state and its motion) is controlled by interaction with laser pulses as exemplified for the case of Be⁺. On the right, a photon is (or several photons are) trapped in a high-Q microwave cavity. The field state is measured and controlled by interaction with highly excited Rb atoms.



Control of individual quantum system

KUNGL. VETENSKAPSAKADEMIEN
THE ROYAL SWEDISH ACADEMY OF SCIENCES

Cavity quantum electrodynamics



How nonclassical states are prepared and how their decoherence can be measured.

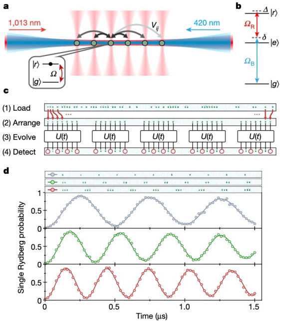
Quantum Computing and Quantum Simulation

ARTICLE

doi:10.1038/nature24622

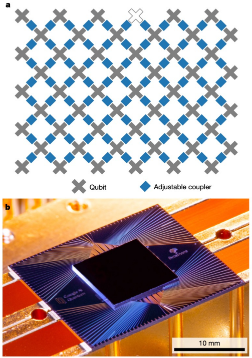
Probing many-body dynamics on a 51-atom quantum simulator

Hannes Bernien[1], Sylvain Schwartz[1,2], Alexander Keesling[1], Harry Levine[1], Ahmed Omran[1], Hannes Pichler[1,3], Soonwon Choi[1], Alexander S. Zibrov[1], Manuel Endres[4], Markus Greiner[1], Vladan Vuletić[2] & Mikhail D. Lukin[1]

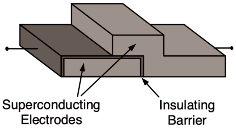


Article

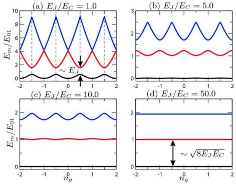
Quantum supremacy using a programmable superconducting processor



Artificial atoms (qubits) with Josephson junctions



Josephson junctions

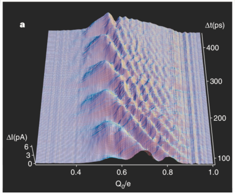


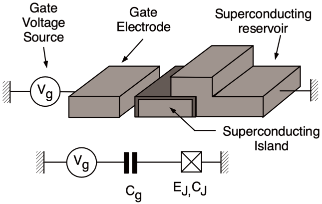

letters to nature

Coherent control of macroscopic quantum states in a single-Cooper-pair box

Y. Nakamura*, Yu. A. Pashkin† & J. S. Tsai*

* *NEC Fundamental Research Laboratories, Tsukuba, Ibaraki 305-8051, Japan*
† *CREST, Japan Science and Technology Corporation (JST), Kawaguchi, Saitama 332-0012, Japan*

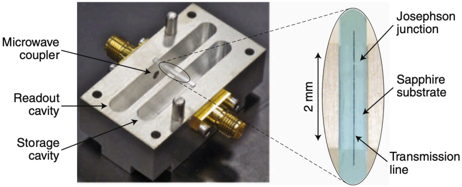


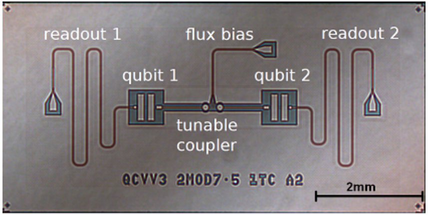


Cooper pair box (charge qubit)

$$\hat{H}(n_g) = \sum_{\mathbf{n}\in\mathbb{Z}} \left[E_C(\mathbf{n}-n_g)^2 |\mathbf{n}\rangle\langle\mathbf{n}| - \frac{E_J}{2}\left(|\mathbf{n}\rangle\langle\mathbf{n}+\mathbf{1}| + |\mathbf{n}+\mathbf{1}\rangle\langle\mathbf{n}|\right)\right]$$

Circuit quantum electrodynamics (cQED) Architectures





Single qubit coupled to a 3D cavity

Superconducting circuit device with two transmon-type qubits

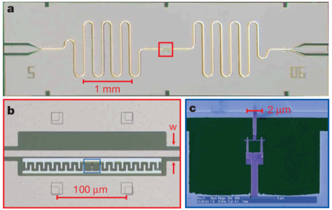
Dispersive regime

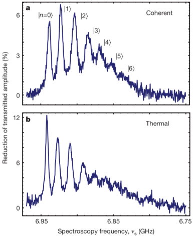

Vol 445 | 1 February 2007 | doi:10.1038/nature05461 nature

LETTERS

Resolving photon number states in a superconducting circuit

D. I. Schuster[1*], A. A. Houck[1*], J. A. Schreier[1], A. Wallraff[1†], J. M. Gambetta[1], A. Blais[1†], L. Frunzio[1], J. Majer[1], B. Johnson[1], M. H. Devoret[1], S. M. Girvin[1] & R. J. Schoelkopf[1]





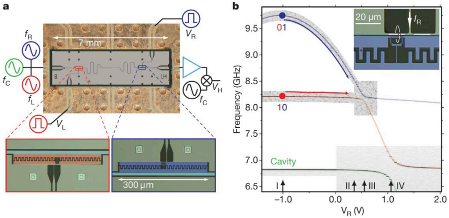
Circuit quantum electrodynamics

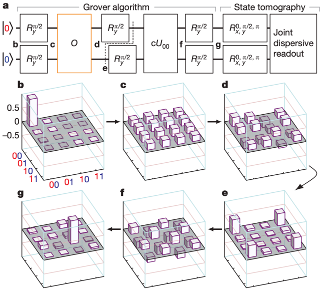
nature Vol 460|9 July 2009|doi:10.1038/nature08121

LETTERS

Demonstration of two-qubit algorithms with a superconducting quantum processor

L. DiCarlo[1], J. M. Chow[1], J. M. Gambetta[2], Lev S. Bishop[1], B. R. Johnson[1], D. I. Schuster[1], J. Majer[3], A. Blais[4], L. Frunzio[1], S. M. Girvin[1] & R. J. Schoelkopf[1]



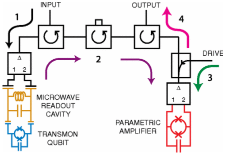


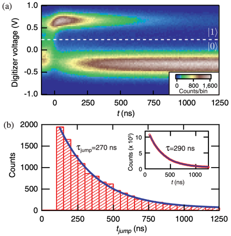
Circuit quantum electrodynamics

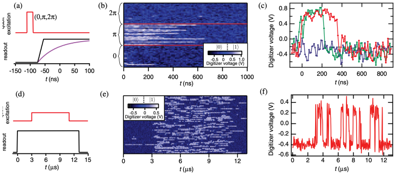
PRL **106,** 110502 (2011) PHYSICAL REVIEW LETTERS week ending 18 MARCH 2011

Observation of Quantum Jumps in a Superconducting Artificial Atom

R. Vijay, D. H. Slichter, and I. Siddiqi
Quantum Nanoelectronics Laboratory, Department of Physics, University of California, Berkeley, California 94720, USA
(Received 29 September 2010; published 14 March 2011)







Circuit quantum electrodynamics

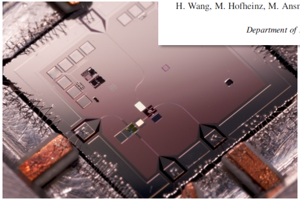
PRL 103, 200404 (2009) PHYSICAL REVIEW LETTERS week ending 13 NOVEMBER 2009

Decoherence Dynamics of Complex Photon States in a Superconducting Circuit

H. Wang, M. Hofheinz, M. Ansmann, R. C. Bialczak, Erik Lucero, M. Neeley, A. D. O'Connell, D. Sank, M. Weides, J. Wenner, A. N. Cleland,* and John M. Martinis†

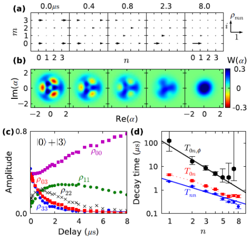
Department of Physics, University of California, Santa Barbara, California 93106, USA

(Received 29 July 2009; published 13 November 2009)

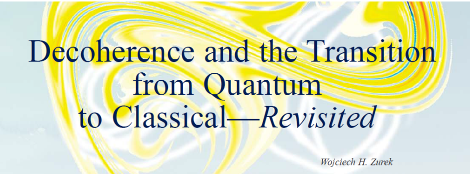


Master equation description of decoherence

$$\frac{d\rho_{mn}}{dt} = -\left[\frac{m+n}{2T_1} + \frac{(m-n)^2}{T_\phi}\right]\rho_{mn} + \frac{\sqrt{(m+1)(n+1)}}{T_1}\rho_{m+1,n+1},$$

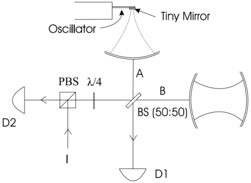


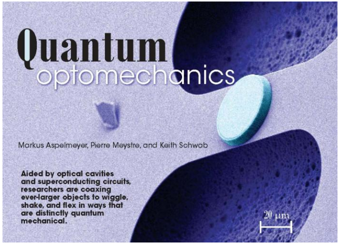
Transition from Quantum to Classical



How to probe decoherence of macroscopic objects

$$H = \hbar\omega_c a^\dagger a + \hbar\omega_m b^\dagger b - \hbar G a^\dagger a(b + b^\dagger),$$

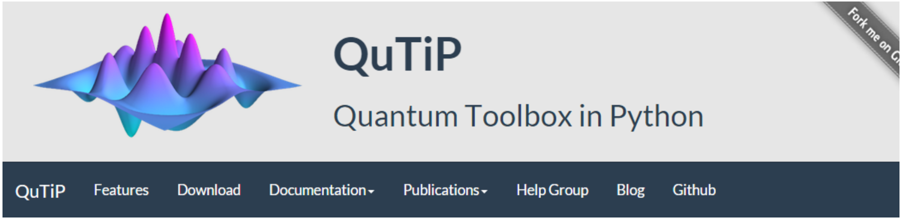




23/03/16

30

Toolbox



Master equation description of decoherence

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Papers Using QuTiP

80. **Lörch** et al., "Sub-Poissonian Phonon Lasing in Three-Mode Optomechanics", arXiv:1502.04112

79. **Dalmonte** et al., "Cluster Luttinger liquids and emergent supersymmetric conformal critical points in the one-dimensional soft-shoulder Hubbard model", arXiv:1502.00396

78. **Weimer**, "Variational analysis of driven-dissipative Rydberg gases", arXiv:1501.07284

77. **Schulte** et al., "Quantum Algorithmic Readout in Multi-Ion Clocks", arXiv:1501.06453

76. **Dalmonte** et al., "Dipolar Spin Models with Arrays of Superconducting Qubits", arXiv:1501.03098

75. **Neilinger** et al., "Two-photon lasing by a superconducting qubit", arXiv:1501.01543

74. **Elliott** et al., "Driving with squeezed vacuum in circuit quantum electrodynamics", arXiv:1501.01009

73. **Borregaard** et al., "Heralded quantum gates with integrated error detection in optical cavitites", arXiv:1501.00956