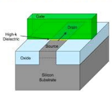
Quantum electrodynamics and quantum optics

Fall 2025

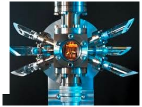
Quantum Science

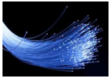
- Quantum theory has affected every day of our lives: atomic clocks for GPS, transistors, optical comm.

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

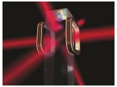
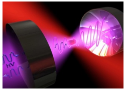
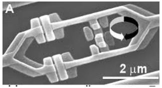


transistors

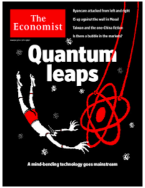

atomic clocks

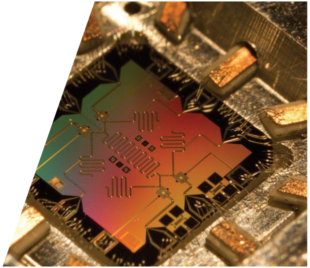

Photoelectric effect

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

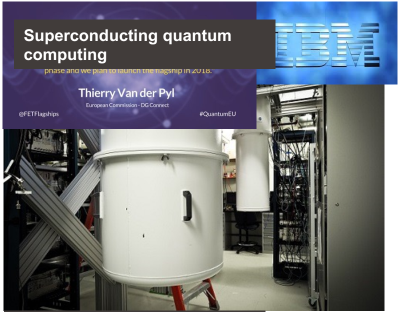




  - Quantum computation
  - Quantum network/communication
  - Quantum simulation
  - Quantum metrology



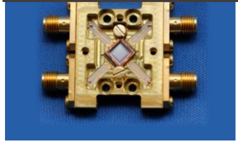


QST potential across disciplines

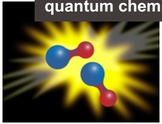


Superconducting quantum computing

Superconducting detectors offer high-speed astronomy



Ultracold molecules for quantum chemistry

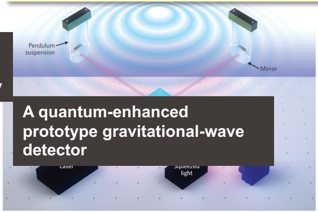


Very active research fields

- 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



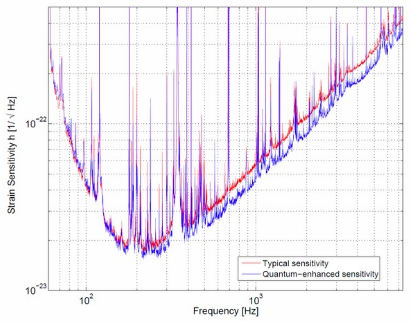
A quantum-enhanced prototype gravitational-wave detector

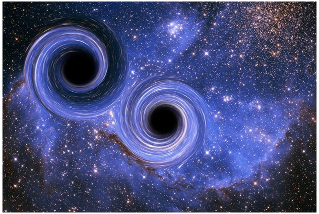
Quantum Science for Precision Measurements

NEWS · 15 FEBRUARY 2019

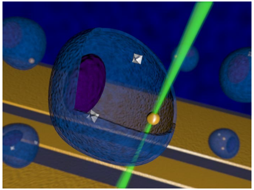
Gravitational-wave observatory LIGO set to double its detecting power

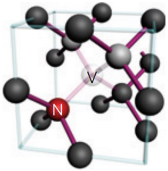
A planned US$35-million upgrade could enable LIGO to spot one black-hole merger per hour by the mid-2020s.

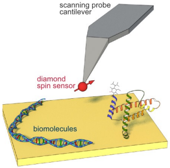




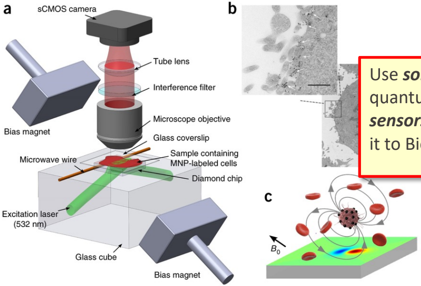
QST potential across disciplines







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



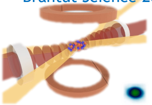
Use ***solid quantum systems*** (e.g. defects in NV) and quantum optics methods to creates ***nanoscale sensors*** for Voltage, Charge, Temperature and apply it to Biology or nanoscale NMR.

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

Experimental Research in QST at EPFL

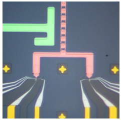
Ultracold atoms Quantum Simulations (Brantut)

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



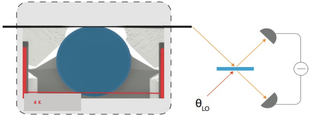
Hybrid Quantum Systems (Scarlino)

- Stockklauser, Scarlino, PRX 2017



Quantum measurements (TJK)

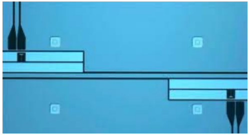
- Wilson, Nature, 2015
- Aspelmeyer Rev. Mod. Phys. 2015



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

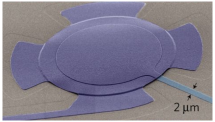
Superconductor Quantum Information (Manucharyan)

Mehta al. Nature (2023)



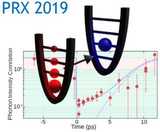
Superconducting quantum optomechanics and qubits

- Youssefi et al. Nature (2022)



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

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

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**.
- Each exercise session (each Thursday 8:15 - 10:00 am) TAs will go through the homework solutions and answer questions.
- Handwritten notes are uploaded to Moodle for reference. We welcome mistake spotting (feedback to TAs). Each lecture TAs will also print the handwritten notes and distribute them in class.

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.
- In week $(n+1)$'s classroom, first a summary will be given of week n's lecture, then Prof. Kippenberg will teach on the blackboard, with step-by-step board work.
- Students should both watch the videos and read the paper of week n before next thursday's course.
- **(tbc)** *Each week a student will present a paper. The presentation should be around 30 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 shuhang.zheng@epfl.ch*

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

Le déroulement du cours permet mon apprentissage et un climat de classe approprié

Sans avis	10%	2
Pas du tout d'accord	14%	3
Pas d'accord	19%	4
D'accord	43%	9
Tout à fait d'accord	14%	3

Remarques

[8 remarque(s)]

- Awesome course on the forefront topics of QED and QO
- I don't like the way that the course is teached. I would prefer to have 4 hours of exercices or 2 hours of course, instead of the 2 hours of lecture review. The course is hard and the low quality of the videos does not help for the learning process.
- Interesting topics. Exercices well structured and help understand the concepts. Blackboard lectures sometimes have errors which is misleading. This course is defenitely worth more than 6ects due to the workload
- It's good. but way to hard. I feel like the time we spend on it could be spent more efficiently. often it feels like we have to derive the equations before the course happens, but since it has not happened yet, we have to spend hours looking at formulas we're not familiar with, where a simple explanation would have sped up the learning process massively. What I'm trying to say is that the learning density for this course is not as high as others. it's a very interesting course though, and the professors explanations are very good.
- reversed class is super hard, this is by far the hardest class I get to pass and it would be much better with a live class in my opinion. It is important so that the teacher can actually see when and where we struggle, and so that we can ask live questions.
- The class is good. However, it would be nice if the TA could come to the TA sessions, because otherwise I don’t have the opportunity to ask questions and progress on this very difficult subject.
- The filmed lectures are hard to follow.
- This course is eclectic and poorly organised. The inverted class is not a problem in itself, but the abysmal quality of the videos, plus the fact that everything is repeated 2 to 3 times is absurd and frustrating. It is extremely complicated to understand what is important and what isn’t. Having just a unified support for the course, like lecture notes that contain everything should be a standard for a class given in this form, instead of requiring us to look for information in ten different places in addition to being supposed to watch 1 to 2 hours of video a week, and series that take up to 5 or 6 hours to complete. It is not an instructive way to learn about something it is only a tedium. Finally, even though the exercises are instructive, the fact that pretty much no assistant is present during the sessions is quite surprising, it is the only course I’ve seen this far to be this way and it is definitely a problem, this added to the inconsistencies at which corrections for the exercises and new series are published means that I went to the exercise session for absolutely no reason a few times. Could we at least get the corrections on time?

Course Comments

Le déroulement du cours permet mon apprentissage et un climat de classe approprié

Sans avis	19%	3
Pas du tout d'accord	13%	2
Pas d'accord	13%	2
D'accord	31%	5
Tout à fait d'accord	25%	4

Remarques

[8 remarque(s)]

- Active learning has advantages and disadvantages. Maybe a more linear treatment of the topics would make them more understandable, especially for new and difficult topics as the wigner representation. Having many reference books may be of help in some cases but it can also generate confusion if the topic is completely new and one is not familiar with different notations and perspectives. The papers and exercise sets are really useful and challenging to the right point
- I personally don't mind the the lecturers 'active teaching' approach and like the way he tries to make us engage actively with the literature. However, the pre recorded lectures we are supposed to watch are of low quality (out of focus blackboard and poor sound-quality) and this needs to be improved, since its our main way of figuring out roughly what we are supposed to learn each week. In addition the difficulty of the course is a bit excessive for a 6 credit course. Doing the mandatory question each week is not too bad, but if you want to properly attempt the full homework, it will take many more hours than the course is properly credited for.
- I really think that this class is very interesting and I personally like the teaching method for the class. The fact is that I have the time to spend on it this semester and I can however understand how it can be difficult for some people to follow it with a 30 credits semester. The main problem that I have is that this teaching method implies in my opinion that the videos should be better quality. Sometimes the sound gets really bad and the video as well. Moreover, I feel like there might not be enough support from the TAs during the exercise session and outside the class. For me a discord channel is not really working and I would prefer a moodle forum where the assistants would be very reactive to answer.
- It's a pity that for such an interesting topic we have a professor that does not enjoy teaching. The provided videos of the lecture are the same thing as going to the 1 hour of summary lecture and they just remain a summary. Hence, we are left to learn ourselves the whole course (which takes a lot of time + the exercises take a lot of time) and we just have a nice summary that outlines what is important. In conclusion, it's not worth taking this course unless you have to. It's definitely not a course to take if you already have a fully charged semester.
- It's a very interesting and very difficult course. The particular methodology doesn't necessarily suit me as I find the recorded lessons very difficult to follow due to the quality of the audio, the image (difficulty in reading the blackboard) and the impossibility of interacting. As a result, the course seems very messy and requires a lot of autonomy/hours of work outside the course given on the blackboard. Even so, the subject is fascinating and well covered.
- The content in the course has been very insightful and interesting. However, it still is a difficult course to follow. I understand and appreciate the "flipped classroom" model, but I feel that the students are

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)
- Prof. Kippenberg will give blackboard lectures in class. This semester the lectures will be more interactive and "live," with a focus on addressing the points where students struggle.
- Each exercise session TAs will go through the homework solutions and answer questions.

Quantum Electrodynamics (QED) effects

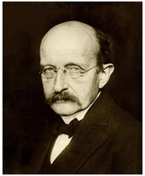
Quantum Electrodynamics (QED) effects

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.

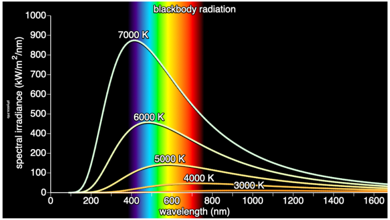


M. Planck, Verhandl. Dtsch. phys. Ges., **2,** 237 **1900**

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

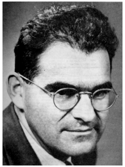
M. Planck
Berlin
(Received 1900)

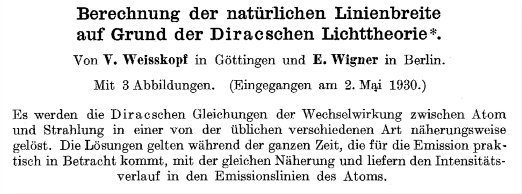
$$B_\nu(\nu,T) = \frac{2h\nu^3}{c^2}\frac{1}{e^{h\nu/kT}-1}$$



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*.

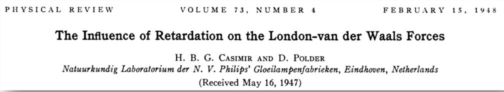
Von **V. Weisskopf** in Göttingen und **E. Wigner** in Berlin.

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.



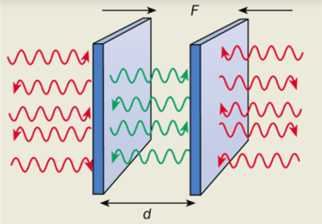
PHYSICAL REVIEW VOLUME 73, NUMBER 4 FEBRUARY 15, 1948

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

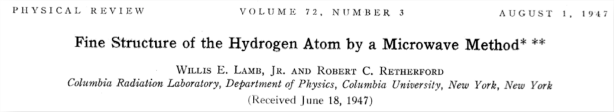
H. B. G. Casimir and D. Polder

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

(Received May 16, 1947)



Quantum Electrodynamics (QED) effects

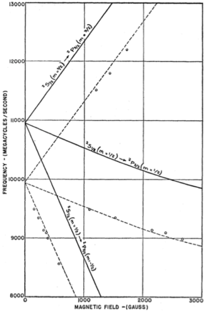

PHYSICAL REVIEW VOLUME 72, NUMBER 3 AUGUST 1, 1947

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

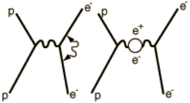
WILLIS E. LAMB, JR. AND ROBERT C. RETHERFORD

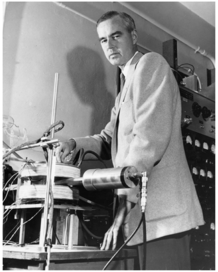
Columbia Radiation Laboratory, Department of Physics, Columbia University, New York, New York

(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..

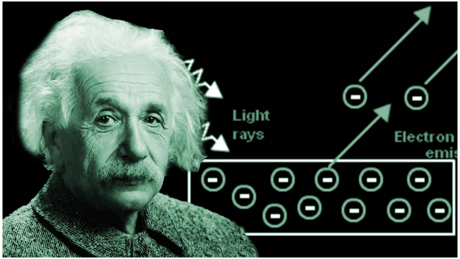


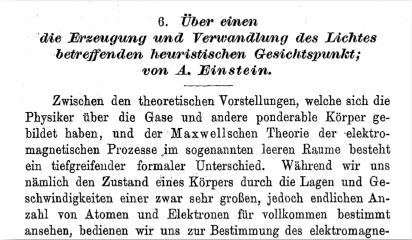


Historical Development of Quantum Optics

Historical Development of Quantum Optics

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



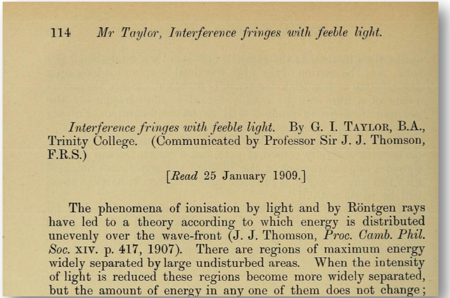


6. *Über einen die Erzeugung und Verwandlung des Lichtes betreffenden heuristischen Gesichtspunkt;*
von A. Einstein.

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

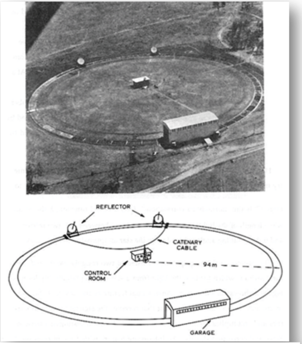


Figure 1. Aerial photo and illustration of the original HBT apparatus. They have been extracted from Ref.[1].

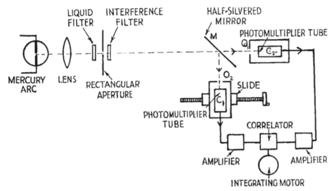


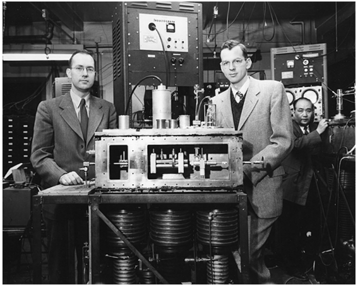
Fig. 2. Simplified diagram of the apparatus

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.

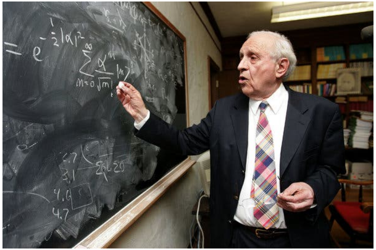


Historical Development of Quantum Optics

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)

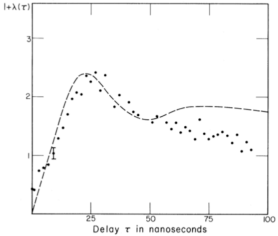
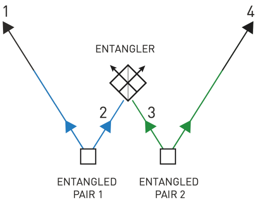


FIG. 3. Values of $1+\lambda(\tau)$ derived from the data. The broken curve shows the theoretically expected form of $\langle \hat{\Gamma}_G(\tau)\rangle$ (with $\Omega/\beta = 4$) for a single atom, arbitrarily normalized to the same peak.

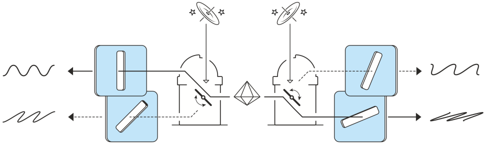
Modern Developments of Quantum Optics

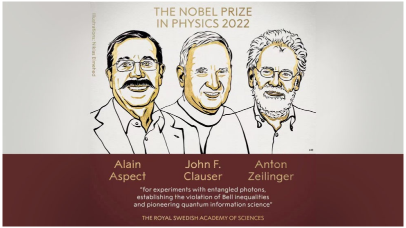
Quantum Entanglement

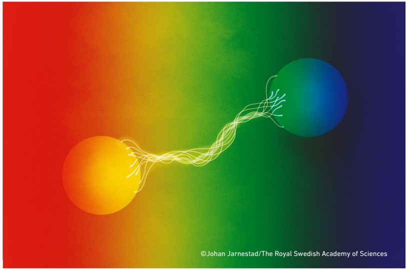
Entangled Photons



Bell Test





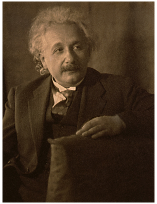


EPR paradox

MAY 15, 1935 PHYSICAL REVIEW VOLUME 47

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

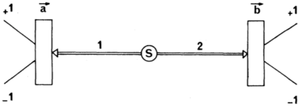
A. Einstein, B. Podolsky and N. Rosen, *Institute for Advanced Study, Princeton, New Jersey*
(Received March 25, 1935)

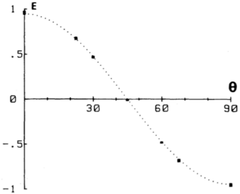


Volume 49, Number 2 PHYSICAL REVIEW LETTERS 12 July 1982

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

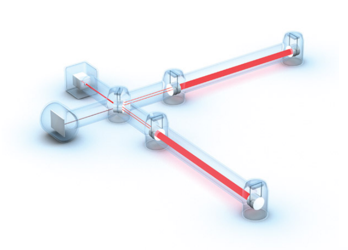
Alain Aspect, Philippe Grangier, and Gérard Roger
Institut d'Optique Théorique et Appliquée, Laboratoire associé au Centre National de la Recherche Scientifique, Université Paris-Sud, F-91406 Orsay, France
(Received 30 December 1981)

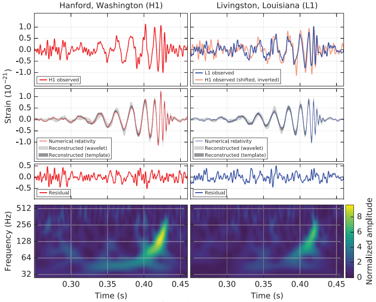




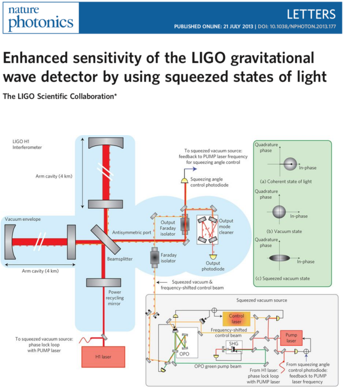
Gravitational wave detection

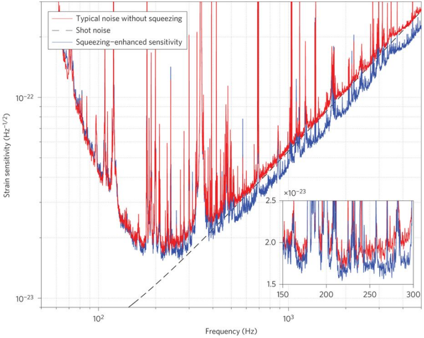
Quantum and thermal noises in gravitational wave detectors



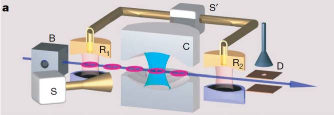


Gravitational wave detection





Cavity quantum electrodynamics



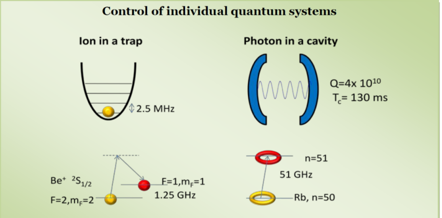
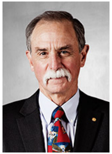


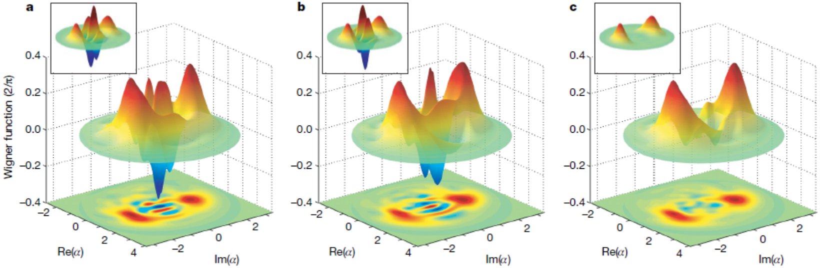
Fig. 1: Illustration of the two types of experiments discussed in this scientific background: On the left, an ion is captured in a harmonic trap. Its quantum state (both its internal state and its motion) is controlled by interaction with laser pulses as exemplified for the case of Be⁺. On the right, 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.

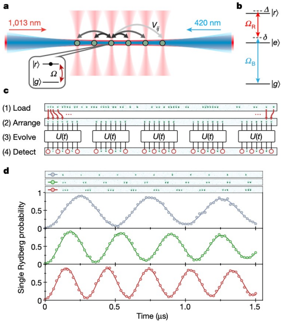
Quantum Computing and Quantum Simulation

ARTICLE

doi:10.1038/nature24622

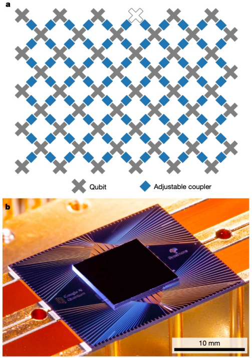
Probing many-body dynamics on a 51-atom quantum simulator

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]

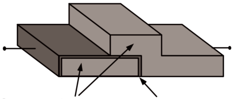


Article

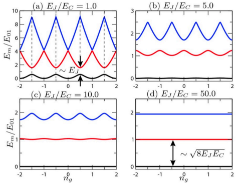
Quantum supremacy using a programmable superconducting processor



Artificial atoms (qubits) with Josephson junctions



Josephson junctions

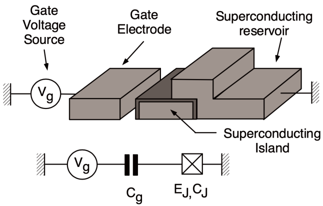


letters to nature

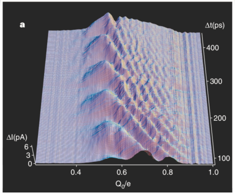
Coherent control of macroscopic quantum states in a single-Cooper-pair box

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

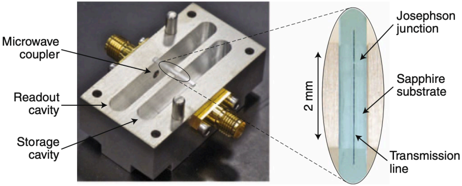


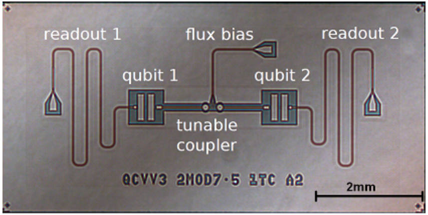
Cooper pair box (charge qubit)



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

Circuit quantum electrodynamics (cQED) Architectures





Single qubit coupled to a 3D cavity

Superconducting circuit device with two transmon-type qubits

Dispersive regime

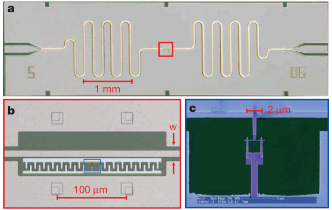
Vol 445 | 1 February 2007 | doi:10.1038/nature05461

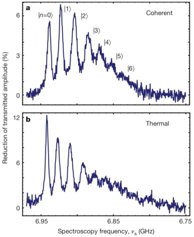
nature

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]





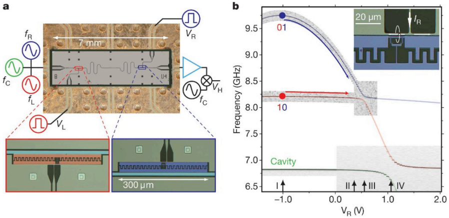
Circuit quantum electrodynamics

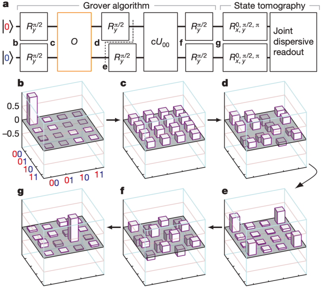
nature Vol 460|9 July 2009|doi:10.1038/nature08121

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]



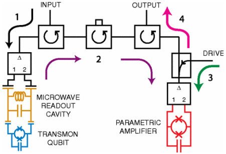


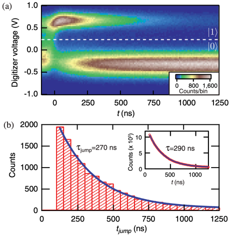
Circuit quantum electrodynamics

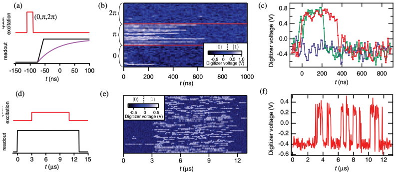
PRL **106,** 110502 (2011) PHYSICAL REVIEW LETTERS week ending 18 MARCH 2011

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)





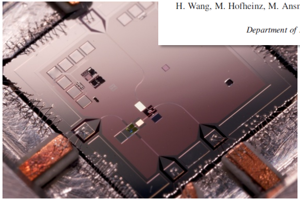


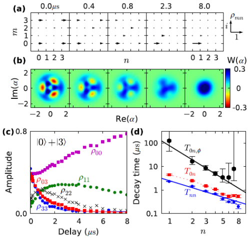
Circuit quantum electrodynamics

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)

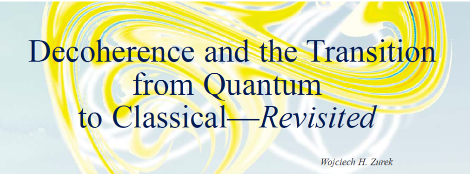




Master equation description of decoherence

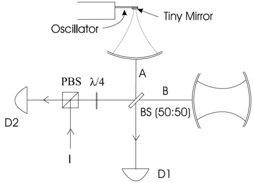
$$\frac{d\rho_{mn}}{dt} = -\left[\frac{m+n}{2T_1} + \frac{(m-n)^2}{T_\phi}\right]\rho_{mn} + \frac{\sqrt{(m+1)(n+1)}}{T_1}\rho_{m+1,n+1},$$

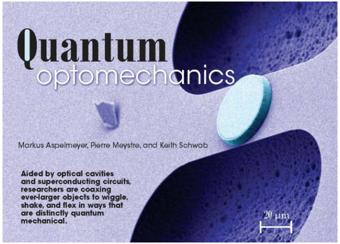
Transition from Quantum to Classical



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

QuTiP

Quantum Toolbox in Python

Fork me on G

QuTiP Features Download Documentation▾ Publications▾ Help Group Blog Github

Master equation description of decoherence

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

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 cavities", arXiv:1501.00956