# Basic research & theoretical physics in Molde

www.himolde.no

Molde University College

Per Kristian Rekdal, 28th September 2012

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# Outline

- Presentation of myself
- Fundametal research
- Quantum optics
- Quantum computers
- Atom chip
- Lifetime ( dehoherence )
- Collaborators
- Summary

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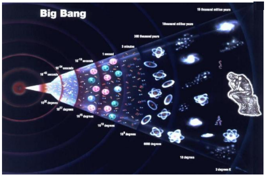
# Presentation

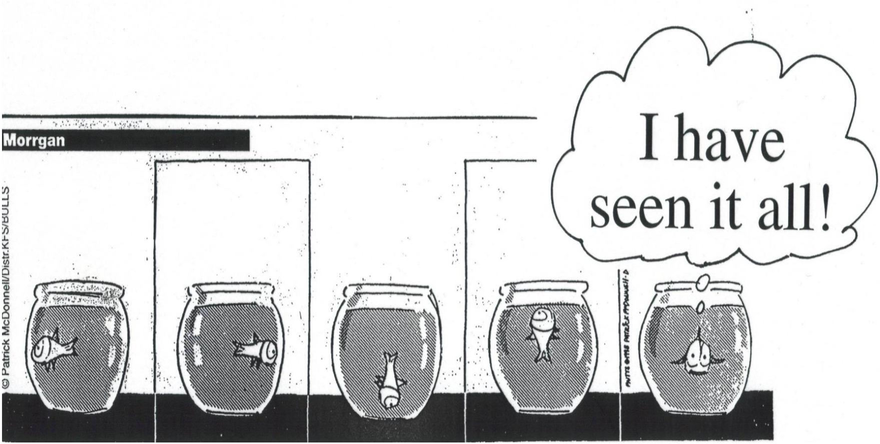
- Name: Per Kristian Rekdal
- Age: 39
- Education:
  - M. Sci.: theoretical physics, NTNU, (1992-1997)
  - Ph.D.: quantum optics, NTNU, (1998-2001)
  - Post Doc: quantum optics, Imperial C., (2002-2004)
  - Post Doc: quantum optics, UniGraz, (2005-2006)
- # published papers: 15
- h-index : 6

Fundamental research: what is it?

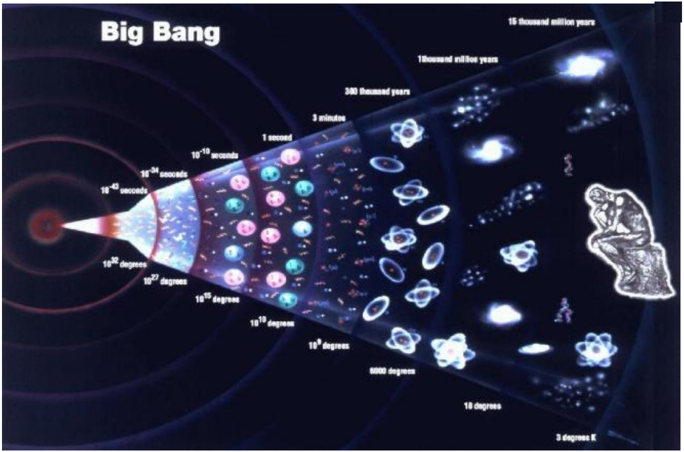
Fundamental research:

- research carried out to increase understanding of fundamental principles
- not intended to yield immediate commercial benefits
- however, in the long term it is the basis for many commercial products and applied research




Morrgan
© Patrick McDonnell/Distr.KFS/BULLS
I have seen it all!

# Big Bang

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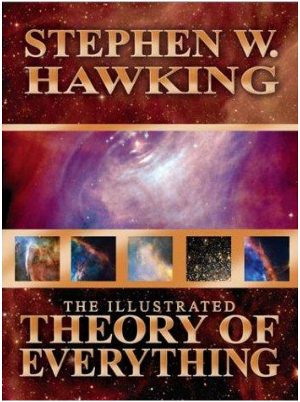
# Theory of everything




$$\mathcal{L} = i\bar{\psi}\gamma^{\mu}\partial_{\mu}\psi - e\bar{\psi}\gamma_{\mu}(A^{\mu} + B^{\mu})\psi - m\bar{\psi}\psi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$

$$\partial_{\mu}\left(\frac{\partial\mathcal{L}}{\partial(\partial_{\mu}\psi)}\right) - \frac{\partial\mathcal{L}}{\partial\psi} = 0$$

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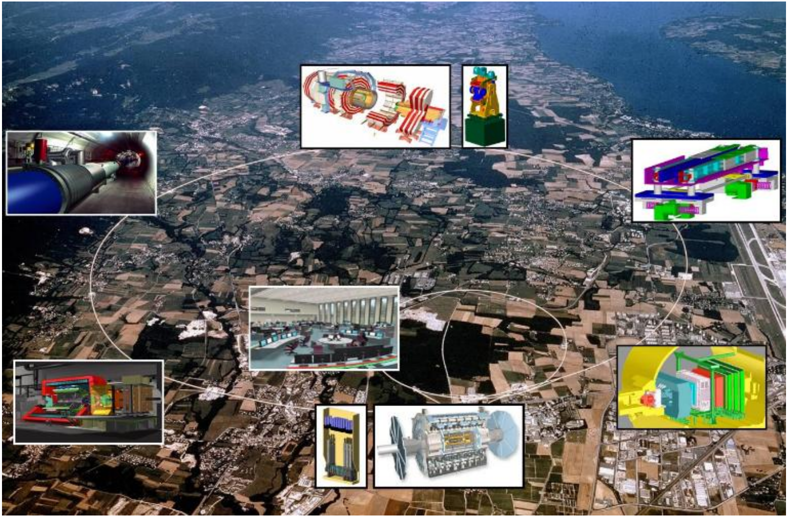
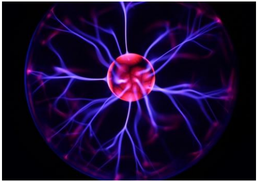
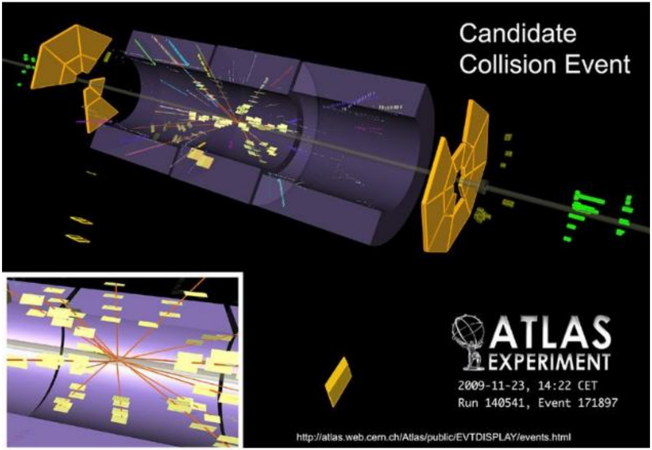
# CERN



# Higgs particle



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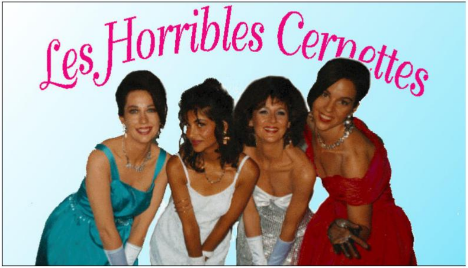
**Dagbladet 12. juli 2012**

Dagbladet.no Kultur
lørdag 15. september 2012
Søk
Nyheter Sport Kultur Kjendis Reise Bil Debatt Magasinet A-A Været dbtv Bestill abonnement Annonsere?
Kultur Film Musikk Litteratur Bokhandel Bokklubb Analog&Digital Tegneserier TV/Medier Scene Kunst Spill Skolekammeret Diktkammeret
Se no Arkiv

annonse






**HISTORISK:** Av alle bilder i verden er dette det første som noensinne ble lagt ut på nettet. Foto: Silvio de Gennaro

# Se det første bildet som noensinne ble publisert på nettet

EMIL FLATØ
efl@dagbladet.no

12.07.2012, kl. 18:54

Amerikanske Vice trykket denne uken historien om det første bildet som noensinne ble publisert på nettet.

**Bildet viser fysikerbandet «Les Horribles Cernettes», eller forkortet LHC, altså partikkelakselleratoren til forskningsgruppen CERN som nylig oppdaget Higgs-bosonet. Den 18. juli er det akkurat 20 år siden bildet ble lagt ut.**

annonse



## Bare fysikere

Forklaringen er enkel:

- I '92-'93 var det nesten bare fysikere som brukte internett, sier Silvio de Gennaro, CERN-fysikeren som tok bildet. Les Horribles Cernettes var et slags husband i forskningsmiljøet.

Så da webutvikleren Jean-François Groff trengte et bilde å legge ut, gikk han bare et par plasser bort på kontoret og fikk Gennaro til å gi ham et bilde av jentegruppen.


Foto: Silvio de Gennaro

## Tilfeldig historieskriving

Det er nok sant som de Gennaro sier det:

- Når historien skrives, vet du ikke at du står i den.

**Historiske «første gang»-hendelser som denne er ofte tilfeldige, skal vi tro ekspertene. Verdens første fotografi var til sammenligning av et tak, sett fra et vindu.**

# Applications, CERN

Dagens Næringsliv — DEBATT — Tirsdag 20. august 1996

Den store feil fremtidsforskere og datafreakere gjør, er å trekke erfaringene fra bruk av PC på arbeidsplassene inne i hjemmene. En slik projisering holder ikke, skriver *Leif Osvold* i Oslo.

DN DEBATT

# Internett en flopp!

Dataeksperter og såkalte fremtidsforskere spår i økende grad at Internett vil bli dominerende i vårt dagligliv i de nærmeste årene, fordi vi vil bli nødt til å ta den i bruk via vår hjemme-PC. Tilbakevisning av slike gale trend-baserte påstander er nå nødvendige, og her er en mot-hypotese: Internett er en flop; det vil si en «motegreie» som kommer til å dø ut om et par år.

Det er tre grunner til dette: 1) ingen av aktørene på nettet vil tjene penger på å legge seg der med sine tilbud, 2) privat bruk av nettet vil være marginalt, og 3) mengden av informasjon på nettet vil bli så enorm at det vil skape frustrerende store søkeproblemer, og dermed frafall av brukere. Hva gjelder punkt en så tror jeg at vi snart vil få se en leverandørflukt fra Internett, når disse oppdager at de har lurt seg selv, redde for ikke å være moderne eller være tilstede der «alle de andre» er.

Hva gjelder punkt 2 så vil jeg ta utgangspunkt i hva flere medieguruer sier. De uttaler at Internett innen år 2000 vil være en like naturlig del av dagliglivet

**Motegreie.** *Internett er en motegreie som kommer til å dø ut om et par år, mener Leif Osvold.*

nelse for arbeidstagerne. Den store feil fremtidsforskerne og datafreakene gjør er imidlertid å trekke erfaringene fra bruk av PC på arbeidsplassene inn i hjemmet. De påstår derfor at en tilsvarende revolusjon vil skje der,

det er bruken av PC som teller, ikke besittelsen. Grunnen til dette er simpelthen at mennesket er et sosialt vesen, og etter en stund kommer til å bli lei av å kommunisere med en maskin i fritiden. PC i hjemmet kommer i all hovedsak til å bli benyttet til jobb- og studie-relaterte oppgaver, samt til spill og underholdning. Og selv volumet av disse positive anvendelsene blir små, også på lang sikt.

Det er forbløffende å konstatere hvordan fremtidsforskere og dataeksperter overser dette fundamentale sosiale element hos mennesket. Det er enkelt å registrere at vi mennesker er slik skapt at vi faktisk ikke ønsker å forholde oss til en datamaskin hele dagen, men at vi trenger å kommunisere med andre levende vesener. Særlig gjelder det dem som bruker PC på jobben. Vi vil derfor ikke benytte en maskin når vi i fritiden skal kommunisere med omverdenen. Vi vil heller ikke sitte alene hjemme og utføre jobben vår, uten kommunikasjon med et kollegialt arbeidsmiljø. Såkalt «fjernarbeid» kommer derfor heller aldri til å bli særlig

vende menneske, ikke taste inn på en maskin. Når vi leier vår video så vil vi besøke utleieren og velge i visuelle omgivelser. Shopping vil vi gjøre ved å oppsøke det levende miljø i butikkene, ikke sitte hjemme og bestille varer. Vi klarer ikke å «snakke» med eksterne familiemedlemmer eller venner via en PC, så lenge vi kan ringe eller besøke dem. Vi vil ikke lese hverken aviser, fag- eller skjønnlitteratur ved å «bla» i en datamaskin, men ved å kjenne papiret og boken i våre egne hender. Disse tingene vil ikke kunne erstattes av «PC-opplevelser», og slik vil det heldigvis fortsette å være, for slik er den menneskelige natur. Kort oppsummert: de sosiale basis-behov hos oss står i direkte motstrid til bruk av datasystemer i hjemmet, og vil naturligvis seire i det lange løp. Og når det gjelder bruk av Internett for å få all verdens informasjon, så tror jeg at dette vil dø ut av seg selv. Vi er allerede overfôret med informasjon, og får dessuten den vi trenger via trykte medier, radio og TV.

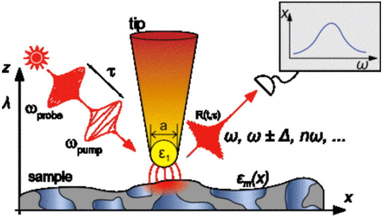
Idag er det kun én prosent av befolkningen som bruker Internett hjemme, og særlig flere tror

# Research

Per Kristian Rekdals field of research: Quantum Optics

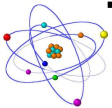
Quantum Optics: (definition)

- light and its interactions with matter
- described by: quantum mechanics

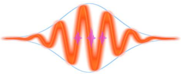


# Atom & Photon: $\Rightarrow$ Quantum Mechanics

Atom:



Photon:



Quantum

Mechanics

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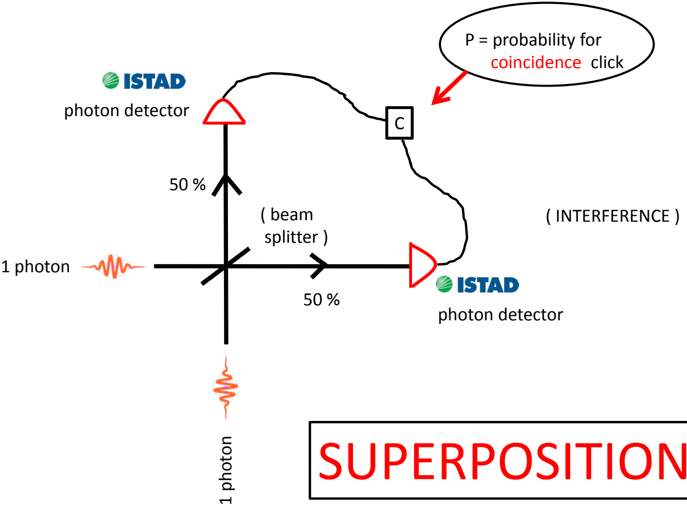
Two quantum properties:

- 1) superposition , adding states $\Rightarrow$ interference
- 2) entanglement , "coupling" of quantum systems




SUPERPOSITION

( sum )

# 2) Entanglement

Electrons:

UP

Pluto

DOWN

Earth

**ENTANGLEMENT**

( coupling )

Video: 04 Entanglement, Dr. Quantum, (1 min. 3 sec.)

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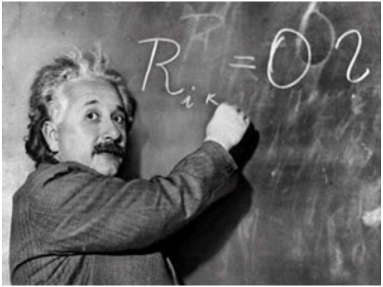
Einstein:

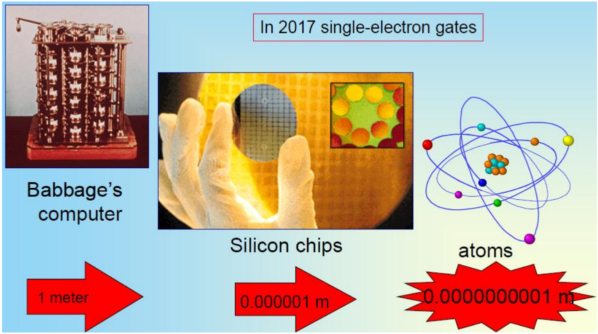
*"Spooky action at a distance"*



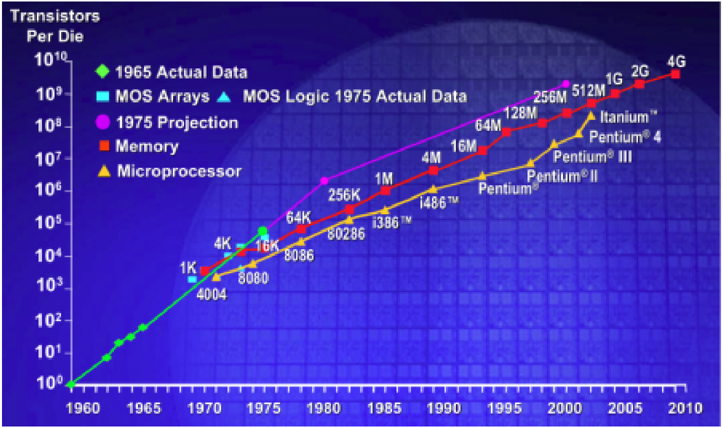
# Many applications!

# Quantum Computer

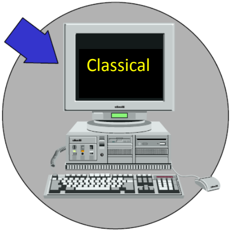

Video: 01 CNN - QC, (2 min. 25 sec.)

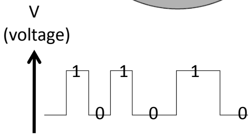

In 2017 single-electron gates
Babbage's computer
Silicon chips
atoms
1 meter
0.000001 m
0.0000000001 m

Moore:
The number of transistors on a chip doubles every $\sim$ two years



# Bit vs Qubit



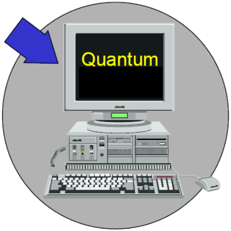



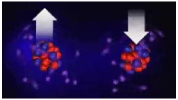

(electric)

## BIT

(classical)

0 OR 1



atom

## QUBIT

(quantum mechanical)

$$|qubit\rangle = \frac{1}{\sqrt{2}}\left[\,|0\rangle + |1\rangle\,\right]$$

Video: 02 Quantum Computers, (2 min.)

# 1) Superposition

a) Classical computer: ($n = 3$ bits register, i.e. $2^n = 8$ alt.)

000 , 001 , 010 , 011 , 100 , 101 , 110 , 111

b) Quantum computer:

$$|\psi\rangle_{in} = c_1|000\rangle + c_2|001\rangle + c_3|010\rangle + c_4|011\rangle + c_5|100\rangle + c_6|101\rangle + c_7|110\rangle + c_8|111\rangle$$

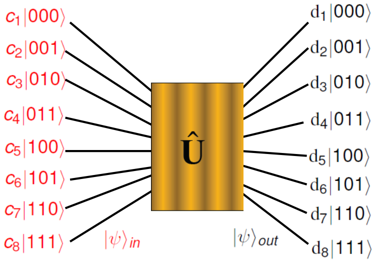
where $\sum_{i=1}^{8} |c_i|^2 = 1$

Unitary operation: ( map )

$$|\psi\rangle_{out} = \hat{U}\,|\psi\rangle_{in}$$

$$= d_1|000\rangle + d_2|001\rangle + d_3|010\rangle + d_4|011\rangle + d_5|100\rangle + d_6|101\rangle + d_7|110\rangle + d_8|111\rangle$$

where $\sum_{i=1}^{8} |d_i|^2 = 1$

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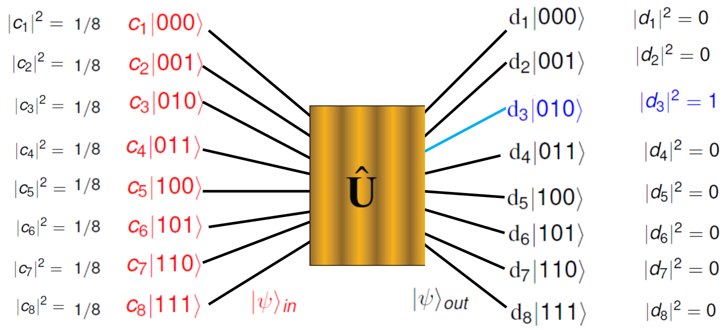
# 1) Superposition (cont.)

## Example:




$( \sum_{i=1}^{8} |c_i|^2 = 1 )$ $( \sum_{i=1}^{8} |d_i|^2 = 1 )$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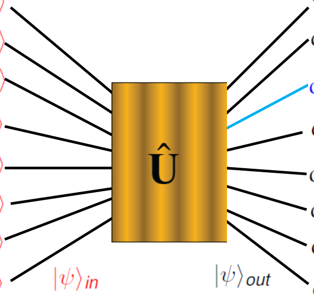
## Example:

| Input probability | Input state | Output state | Output probability |
|---|---|---|---|
| $|c_1|^2 = 1/8$ | $c_1|000\rangle$ | $d_1|000\rangle$ | $|d_1|^2 = 0$ |
| $|c_2|^2 = 1/8$ | $c_2|001\rangle$ | $d_2|001\rangle$ | $|d_2|^2 = 0$ |
| $|c_3|^2 = 1/8$ | $c_3|010\rangle$ | $d_3|010\rangle$ | $|d_3|^2 = 1$ |
| $|c_4|^2 = 1/8$ | $c_4|011\rangle$ | $d_4|011\rangle$ | $|d_4|^2 = 0$ |
| $|c_5|^2 = 1/8$ | $c_5|100\rangle$ | $d_5|100\rangle$ | $|d_5|^2 = 0$ |
| $|c_6|^2 = 1/8$ | $c_6|101\rangle$ | $d_6|101\rangle$ | $|d_6|^2 = 0$ |
| $|c_7|^2 = 1/8$ | $c_7|110\rangle$ | $d_7|110\rangle$ | $|d_7|^2 = 0$ |
| $|c_8|^2 = 1/8$ | $c_8|111\rangle$ | $d_8|111\rangle$ | $|d_8|^2 = 0$ |




$( \sum_{i=1}^{8} |c_i|^2 = 1 )$

$( \sum_{i=1}^{8} |d_i|^2 = 1 )$

constructive / destructive interference

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# 1) Superposition (cont.)

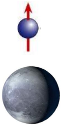
Quantum computer: massive parallelism

Video: 03 QC, traveling sales man, (stop at 2 min.)

# 2) Entanglement

## Electrons:

UP



Pluto

DOWN

Earth

**ENTANGLEMENT**

( coupling )

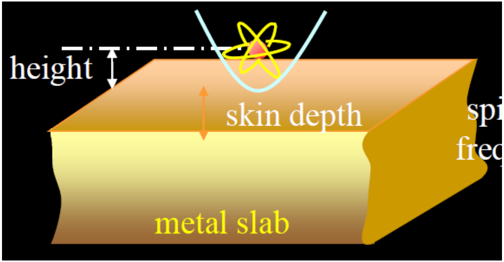
Video: 05 Entanglement, The Weirdness Of QM, (stop at 3 min. 27 sec.)

# Applications of QC

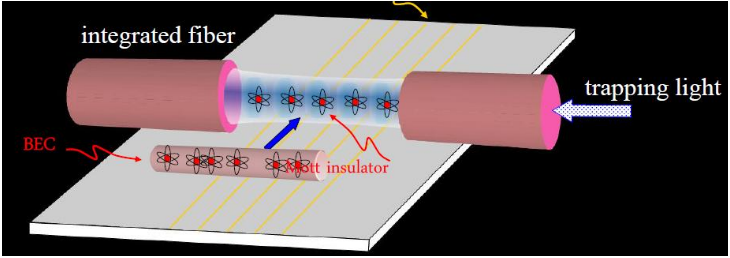
- Faster calculations
- Perform detailed search more quickly
  - seach in a database
  - traveling salesman
- simulate molecules for improvement of:
  - medical properties
  - superconductor
  - nanotechnology
- Quantum cryptography
  - credit cards
  - military secrets
  - Shor's algorithm
- lasers
- sensors

Video: : 06 What is a QC + applications, (stop at: 3 min. 13 sec.)

# Atom Chip



# Atom Chip



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## Physicists entangle a record-breaking 14 quantum bits

By John Matson | Apr 5, 2011 04:18 PM | 5

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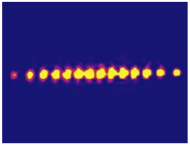

Quantum information science is a bit like classroom management—the larger the group, the harder it is to keep everything together.

But to build a practical quantum computer physicists will need many particles working in synchrony as quantum bits, or qubits. Each qubit can be a 0 and a 1 simultaneously, vaulting the number-crunching power of a hypothetical quantum computer well past that of ordinary computers. With each qubit in a superposition, a quantum computer can manipulate an exponentially large quantity of numbers at once—$2^n$ numbers for a system of $n$ qubits. So each step toward generating large sets of qubits pushes practical quantum computing closer to reality.

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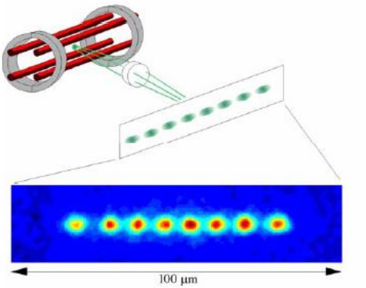
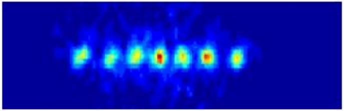
Zoo of quantum optics systems

# Zoo of quantum optics systems

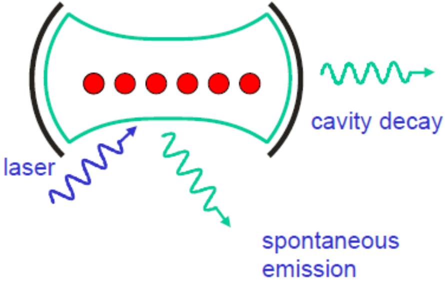
Ions in magnetic traps: ( quantum register )



collective modes

Atoms trapped in a cavity: (atoms are qubits)

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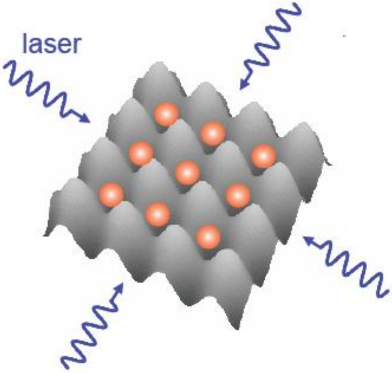
Optical lattice as array of microtraps for atoms:



Decoherence

( loss of superposition , loss of ordering )

PRL **97,** 070401 (2006) PHYSICAL REVIEW LETTERS week ending 18 AUGUST 2006

## Spin Decoherence in Superconducting Atom Chips

Bo-Sture K. Skagerstam,[1,*] Ulrich Hohenester,[2] Asier Eiguren,[2] and Per Kristian Rekdal[2,†]

[1]*Complex Systems and Soft Materials Research Group, Department of Physics, The Norwegian University of Science and Technology, N-7491 Trondheim, Norway*

[2]*Institut für Physik, Karl-Franzens-Universität Graz, Universitätsplatz 5, A-8010 Graz, Austria*

(Received 25 March 2006; published 16 August 2006)

Using a consistent quantum-mechanical treatment for the electromagnetic radiation, we theoretically investigate the magnetic spin-flip scatterings of a neutral two-level atom trapped in the vicinity of a superconducting body. We derive a simple scaling law for the corresponding spin-flip lifetime for such an atom trapped near a superconducting thick slab. For temperatures below the superconducting transition temperature $T_c$, the lifetime is found to be enhanced by several orders of magnitude in comparison to the case of a normal conducting slab. At zero temperature the spin-flip lifetime is given by the unbounded free-space value.

DOI: 10.1103/PhysRevLett.97.070401 PACS numbers: 03.65.Yz, 03.75.Be, 34.50.Dy, 42.50.Ct

# Decoherence

PRL 97, 070401 (2006) PHYSICAL REVIEW LETTERS week ending 18 AUGUST 2006

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DOI: 10.1103/PhysRevLett.97.070401 PACS numbers: 03.65.Yz, 03.75.Be, 34.50.Dy, 42.50.Ct

Coherent manipulation of matter waves is one of the ultimate goals of atom optics. Trapping and manipulating cold neutral atoms in microtraps near surfaces of atomic chips is a promising approach towards full control of matter waves on small scales [1]. The subject of atom optics is making rapid progress, driven both by the fundamental interest in quantum systems and by the prospect of new devices based on quantum manipulations of neutral atoms.

With lithographic or other surface-patterning processes complex atom chips can be built which combine many traps, waveguides, and other elements, in order to realize controllable composite quantum systems [2] as needed, e.g., for the implementation of quantum information devices [3]. Such microstructured surfaces have been highly successful and form the basis of a growing number of experiments [4]. However, due to the proximity of the cold atom cloud to the macroscopic substrate additional decoherence channels are introduced which limit the performance of such atom chips. Most importantly, Johnson-noise currents in the material cause electromagnetic field fluctuations and hence threaten to decohere the quantum state of the atoms. This effect arises because the finite temperature and resistivity of the surface material are always accompanied by field fluctuations, as a consequence of the fluctuation-dissipation theorem. Several experimental [5–7] as well as theoretical [8–11] studies have recently shown that rf spin-flip transitions are the main source of decoherence for atoms situated close to metallic or dielectric bodies. Upon making spin-flip transitions, the atoms become more weakly trapped or even lost from the microtrap.

In Ref. [10] it was shown that to reduce the spin decoherence of atoms outside a metal in the normal state, one should avoid materials whose skin depth at the spin-flip transition frequency is comparable with the atom-surface distance. For typical values of these parameters used in experiments, however, this worst-case scenario occurs [5–7]. To overcome this deficiency, it was envisioned [9] that superconductors might be beneficial in this respect because of their efficient screening properties, although this conclusion was not backed by a proper theoretical analysis. It is the purpose of this letter to present a consistent theoretical description of atomic spin-flip transitions in the vicinity of superconducting bodies, using a proper quantum-mechanical treatment for the electromagnetic radiation, and to reexamine Johnson-noise induced decoherence for superconductors. We find that below the superconducting transition temperature $T_c$ the spin-flip lifetime becomes boosted by several orders of magnitude, a remarkable finding which is attributed to: (1) the opening of the superconducting gap and the resulting inability to deposit energy into the superconductor, (2) the highly efficient screening properties of superconductors, and (3) the small active volume within which current fluctuations can contribute to field fluctuations. Our results thus suggest that current-noise induced decoherence in atomic chips can be completely diminished by using superconductors instead of normal metals.

We begin by considering an atom in an initial state $|i\rangle$ and trapped at position $\mathbf{r}_A$ in vacuum, near a dielectric body. The rate of spontaneous and thermally stimulated magnetic spin-flip transition into a final state $|f\rangle$ has been derived in Ref. [10],

$$\Gamma^B = \mu_0 \frac{2(\mu_B g_S)^2}{\hbar} \sum_{j,k=1}^{3} \langle f|\hat{S}_j|i\rangle\langle i|\hat{S}_k|f\rangle \times \mathrm{Im}[\nabla \times \nabla \times \boldsymbol{G}(\mathbf{r}_A, \mathbf{r}_A, \omega)]_{jk}(\bar{n}_{\mathrm{th}} + 1). \quad (1)$$

Here $\mu_B$ is the Bohr magneton, $g_s \approx 2$ is the electron spin $g$ factor, $\langle f|\hat{S}_j|i\rangle$ is the matrix element of the electron spin operator corresponding to the transition $|i\rangle \rightarrow |f\rangle$, and $\boldsymbol{G}(\mathbf{r}_A, \mathbf{r}_A, \omega)$ is the dyadic Green tensor of Maxwell's theory. Equation (1) follows from a consistent quantum-mechanical treatment of electromagnetic radiation in the

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# Decoherence



presence of absorbing bodies [11,12]. Thermal excitations of the electromagnetic field modes are accounted for by the factor ($\bar{n}_{\rm th}+1$), where $\bar{n}_{\rm th} = 1/(e^{\hbar\omega/k_BT}-1)$ is the mean number of thermal photons per mode at frequency $\omega$ of the spin-flip transition. The dyadic Green tensor is the unique solution to the Helmholtz equation

$$\nabla \times \nabla \times \boldsymbol{G}(\mathbf{r}, \mathbf{r}', \omega) - k^2 \epsilon(\mathbf{r}, \omega)\boldsymbol{G}(\mathbf{r}, \mathbf{r}', \omega) = \delta(\mathbf{r} - \mathbf{r}')\mathbf{1}, \qquad (2)$$

with appropriate boundary conditions. Here $k = \omega/c$ is the wave number in vacuum, $c$ is the speed of light and **1** the unit dyad. This quantity contains all relevant information about the geometry of the material and, through the electric permittivity $\epsilon(\mathbf{r}, \omega)$, about its dielectric properties.

The current density in superconducting media is commonly described by the Mattis-Bardeen theory [13]. To simplify the physical picture, let us limit the discussion to low but nonzero frequencies $0 < \omega \ll \omega_g \equiv 2\Delta(0)/\hbar$, where $\omega$ is the angular frequency and $\Delta(0)$ is the energy gap of the superconductor at zero temperature. In this limit, the current density is well described by means of a two-fluid model [14,15]. At finite temperature $T$, the current density consists of two types of carriers, superconducting Cooper pairs and normal conducting electrons. The total current density is equal to the sum of a superconducting current density and a normal conducting current density, i.e., $\mathbf{J}(\mathbf{r}, t) = \mathbf{J}_s(\mathbf{r}, t) + \mathbf{J}_n(\mathbf{r}, t)$. Let us furthermore assume that the superconducting as well as the normal conducting part of the current density responds linearly and locally to the electric field [16], in which case the current densities are given by the London equation and Ohm's law, respectively,

$$\frac{\partial \mathbf{J}_s(\mathbf{r}, t)}{\partial t} = \frac{\mathbf{E}(\mathbf{r}, t)}{\mu_0 \lambda_L^2(T)}, \qquad \mathbf{J}_n(\mathbf{r}, t) = \sigma_n(T)\mathbf{E}(\mathbf{r}, t). \quad (3)$$

The London penetration length and the normal conductivity are given by,

$$\lambda_L^2(T) = \frac{m}{\mu_0 n_s(T) e^2}, \qquad \sigma_n(T) = \frac{n_n(T)}{n_0}\sigma. \quad (4)$$

Here $\sigma$ is the electrical conductivity of the metal in the normal state, $m$ is the electron mass, $e$ is the electron charge, and $n_s(T)$ and $n_n(T)$ are the electron densities in the superconducting and normal state, respectively, at a given temperature $T$. Following London [14], we assume that the total density is constant and given by $n_0 = n_s(T) + n_n(T)$, where $n_s(T) = n_0$ for $T = 0$ and $n_n(T) = n_0$ for $T > T_c$. For a London superconductor with the assumptions as mentioned above, the dielectric function $\epsilon(\omega)$ in the low-frequency regime reads

$$\epsilon(\omega) = 1 - \frac{1}{k^2\lambda_L^2(T)} + i\frac{2}{k^2\delta^2(T)}, \qquad (5)$$

where $\delta(T) \equiv \sqrt{2/\omega\mu_0\sigma_n(T)}$ is the skin depth associated with the normal conducting electrons. The optical conductivity corresponding to Eq. (5) is $\sigma(T) = 2/\omega\mu_0\delta^2(T) + i/\omega\mu_0\lambda_L^2(T)$.

In the following we apply our model to the geometry shown in Fig. 1, where an atom is located in vacuum at a distance $z$ away from a superconducting slab. We consider, in correspondence to recent experiments [5–7], $^{87}$Rb atoms that are initially pumped into the $|5S_{1/2}, F = 2, m_F = 2\rangle \equiv |2, 2\rangle$ state. Fluctuations of the magnetic field may then cause the atoms to evolve into hyperfine sublevels with lower $m_F$. Upon making a spin-flip transition to the $m_F = 1$ state, the atoms are more weakly trapped and are largely lost from the region of observation, causing the measured atom number to decay with rate $\Gamma_{21}^B$ associated with the rate-limiting transition $|2, 2\rangle \to |2, 1\rangle$. The transition rate $\Gamma_{21}^B = (\Gamma_{21}^0 + \Gamma_{21}^{\rm slab})(\bar{n}_{\rm th} + 1)$ can be decomposed into a free part and a part purely due to the presence of the slab. The free-space spin-flip rate at zero temperature is $\Gamma_{21}^0 = \mu_0 \frac{(\mu_B g_S)^2}{24\pi\hbar} k^3$ [10]. The slab-contribution can be obtained by matching the electromagnetic fields at the vacuum-superconductor interface. With the same spin orientation as in Ref. [9], i.e., $|\langle f|\hat{S}_y|i\rangle|^2 = |\langle f|\hat{S}_z|i\rangle|^2$ and $\langle f|\hat{S}_x|i\rangle = 0$, the spin-flip rate is $\Gamma_{21}^{\rm slab} = \Gamma_{21}^0(\tilde{I}_\parallel + \tilde{I}_\perp)$, with the atom-spin-orientation dependent integrals

$$\tilde{I}_\parallel = \frac{3}{8}\,\mathrm{Re}\left(\int_0^\infty dq \frac{q}{\tilde{\eta}_0} e^{i2\tilde{\eta}_0 kz}[r_p(q) - \tilde{\eta}_0^2 r_s(q)]\right), \qquad (6)$$

$$\tilde{I}_\perp = \frac{3}{4}\,\mathrm{Re}\left(\int_0^\infty dq \frac{q^3}{\tilde{\eta}_0} e^{i2\tilde{\eta}_0 kz} r_s(q)\right), \qquad (7)$$

and the electromagnetic field polarization dependent Fresnel coefficients

$$r_s(q) = \frac{\tilde{\eta}_0 - \tilde{\eta}(\omega)}{\tilde{\eta}_0 + \tilde{\eta}(\omega)}, \qquad r_p(q) = \frac{\epsilon(\omega)\tilde{\eta}_0 - \tilde{\eta}(\omega)}{\epsilon(\omega)\tilde{\eta}_0 + \tilde{\eta}(\omega)}. \quad (8)$$

Here we have $\tilde{\eta}(\omega) = \sqrt{\epsilon(\omega) - q^2}$ and $\tilde{\eta}_0 = \sqrt{1 - q^2}$. In

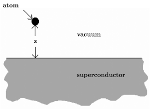


FIG. 1. Schematic picture of the setup considered in our calculations. An atom inside a magnetic microtrap is located in vacuum at a distance $z$ away from a thick superconducting slab, i.e., a semi-infinite plane. Upon making a spin-flip transition, the atom becomes more weakly trapped and is eventually lost.

# Decoherence



particular, above the transition temperature $T_c$ the dielectric function in Eq. (5) reduces to the well-known Drude form. Because of the efficient screening properties of superconductors, in most cases of interest the inequality $\lambda_L(T) \ll \delta(T)$ holds. Assuming furthermore the near-field case $\lambda_L(T) \ll z \ll \lambda$, where $\lambda = 2\pi/k$ is the wavelength associated to the spin-flip transition, which holds true in practically all cases of interest, we can compute the integrals in Eqs. (6)–(8) analytically to finally obtain

$$\Gamma_{21}^B \approx \Gamma_{21}^0(\bar{n}_{\rm th}+1)\left[1+2\left(\frac{3}{4}\right)^3 \frac{1}{k^3\delta(T)^2}\frac{\lambda_L^3(T)}{z^4}\right]. \quad (9)$$

For a superconductor at $T = 0$, in which case there are no normal conducting electrons, it is seen from Eq. (9) that the lifetime is given by the unbounded free-space lifetime $\tau_0 = 1/\Gamma_{21}^0$.

Equation (9) is the central result of our Letter. To inquire into its details, we compute the spin-flip rate for the superconductor niobium (Nb) and for a typical atomic transition frequency $\nu \equiv \omega/2\pi = 560$ kHz [5]. We keep the atom-surface distance fixed at $z = 50\ \mu$m, and use the Gorter-Casimir [15] temperature dependence

$$\frac{n_s(T)}{n_0} = 1 - \frac{n_n(T)}{n_0} = 1 - \left(\frac{T}{T_c}\right)^4, \quad (10)$$

for the superconducting electron density. Figure 2 shows the spin-flip lifetime $\tau_s \equiv 1/\Gamma_{21}^B$ of the atom as a function of temperature: over a wide temperature range $\tau_s$ remains as large as $10^{10}$ sec. In comparison to the normal-metal lifetime $\tau_n$, which is obtained for aluminum with its quite small skin depth $\delta = 110\ \mu$m and using the results of Refs. [9,10], we observe that the lifetime becomes boosted by almost 10 orders of magnitude in the superconducting state. In particular, for $T = 0$ the ratio between $\tau_s$ and $\tau_n$ is even $10^{17}$. From the scaling behavior Eq. (9) we thus observe that decoherence induced by current fluctuations in the superconducting state remains completely negligible even for small atom-surface distances around 1 $\mu$m, in strong contrast to the normal state where such decoherence would limit the performance of atomic chips.

The scaling behavior of the spin-flip rate Eq. (9) can be understood qualitatively on the basis of Eq. (1). The fluctuation-dissipation theorem [11,12] relates the imaginary part of the Green tensor and $\epsilon(\omega)$ by Im$\mathbf{G} = \mathbf{G}\,{\rm Im}[\epsilon(\omega)]\mathbf{G}^*$, assuming a suitable real-space convolution, and allows to bring the scattering rate Eq. (1) to a form reminiscent of Fermi's golden rule. The magnetic dipole of the atom at $\mathbf{r}_A$ couples to a current fluctuation at point $\mathbf{r}$ in the superconductor through $\boldsymbol{G}(\mathbf{r}_A, \mathbf{r}, \omega)$. The propagation of the current fluctuation is described by the dielectric function $\epsilon(\omega)$, and finally a backaction on the atomic dipole occurs via $\boldsymbol{G}(\mathbf{r}, \mathbf{r}_A, \omega)$. For the near-field coupling under consideration, $z \ll \lambda$, the dominant contribution of the Green tensor is $|\mathbf{G}| \sim 1/z^2$, thus resulting in the overall $z^{-4}$ dependence of the spin-flip rate Eq. (9).

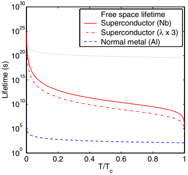


FIG. 2 (color online). Spin-flip lifetime of a trapped atom near a superconducting slab $\tau_s$ (red solid line) as a function of temperature $T$. The atom-surface distance is fixed at $z = 50\ \mu$m, and the frequency of the atomic transition is $\nu = 560$ kHz. The other parameters are $\lambda_L(0) = 35$ nm [19], $\sigma \approx 2\times10^9\ (\Omega\,{\rm m})^{-1}$ [20], and $T_c = 8.31$ K [19], corresponding to superconducting Nb. The numerical value of $\tau_s$ is computed using the temperature dependence as given by Eq. (10). As a reference, we have also plotted the lifetime $\tau_n$ (blue dashed line) for an atom outside a normal conducting slab with $\delta = 110\ \mu$m, corresponding to Al. The red dashed-dotted line is the lifetime for the same parameters as mentioned above but $\lambda_L(0) = 3\times 35$ nm, i.e., where we have taken into account the fact that the London length is modified due to nonlocal effects. The dotted line corresponds to the lifetime $\tau_0/(\bar{n}_{\rm th}+1)$ for a perfect normal conductor. The unbounded free-space lifetime at zero temperature is $\tau_0 \approx 10^{25}$ s.

The imaginary part ${\rm Im}[\epsilon(\omega)] \sim 1/\delta^2$ of the dielectric function Eq. (5) accounts for the loss of electromagnetic energy to the superconductor, and is only governed by electrons in the normal state, whereas electrons in the superconducting state cannot absorb energy because of the superconducting gap. Finally, the term $\lambda^3$ is due to the dielectric screening $1/\epsilon(\omega) \sim \lambda^2$ of the charge fluctuation seen by the atom, and an additional $\lambda$ contribution associated to the active volume of current fluctuations which contribute to the magnetic field fluctuations at the position of the atom. Fluctuations deeper inside the superconductor are completely screened out. In comparison to the corresponding scaling $\Gamma^B \sim \delta/z^4$ for a normal metal [9], which can be qualitatively understood by a similar reasoning, the drastic lifetime enhancement in the superconducting state is thus due to the combined effects of the opening of the superconducting gap, the highly efficient screening, and the small active volume.

Let us finally briefly comment on the validity of our simplified approach, and how our results would be modi-

# Decoherence



fied if using a more refined theory for the description of the superconductor. Our theoretical approach is valid in the same parameter regime as London's theory, that is $\lambda(T) \gg \xi(T)$. It is well known that nonlocal effects modify the London length in Nb from $\lambda_L(0) \approx 35$ nm to $\lambda(0) \approx 90$ nm [17], and the coherence length $\xi(T)$, according to Pippard's theory [18], from the BCS value $\xi_0$ to $1/\xi(T) = 1/\xi_0 + 1/\alpha\ell(T)$, where $\alpha$ is of the order one and $l(T)$ is the mean free path. For Nb, $\xi_0 = 39$ nm and $l(T \leq 9\text{ K}) \cong 9$ nm [19], and the London condition $\lambda(T) \gg \xi(T)$ is thus satisfied. Furthermore, at the atomic transition frequency the conductivity is $\sigma \approx 2 \times 10^9\ (\Omega\,\text{m})^{-1}$ [20] and the corresponding skin depth is $\delta = \sqrt{2/\omega\mu_0\sigma} \approx 15\ \mu\text{m} \leq \delta(T)$, such that Ohm's law is also valid since $\delta(T) \gg l(T)$ [21]. It is important to realize that other possible modifications of the parameters used in our calculations, as, e.g., a modification of Eq. (10) for $T/T_c \lesssim 0.5$ [22,23] will by no means drastically change our findings, which only rely on the generic superconductor properties of the efficient screening and the opening of the energy gap, and that our conclusions will also prevail for other superconductor materials.

We also mention that for both a superconductor at $T = 0$ and a perfect normal conductor, i.e. $\delta = 0$, the lifetime is given by the unbounded free-space lifetime $\tau_0$. In passing, we notice that for an electric dipole transition and for a perfect normal conductor, as, e.g., discussed in Refs. [24], the correction to the vacuum rate is in general opposite in sign as compared to that of a magnetic dipole transition. Elsewhere decay processes in the vicinity of a thin superconducting film will be discussed in detail [25].

To summarize, we have used a consistent quantum theoretical description of the magnetic spin-flip scatterings of a neutral two-level atom trapped in the vicinity of a superconducting body. We have derived a simple scaling law for the corresponding spin-flip lifetime for a superconducting thick slab. For temperatures below the superconducting transition temperature $T_c$, the lifetime has been found to be enhanced by several orders of magnitude in comparison to the case of a normal conducting slab. We believe that this result represents an important step towards the design of atomic chips for high-quality quantum information processing.

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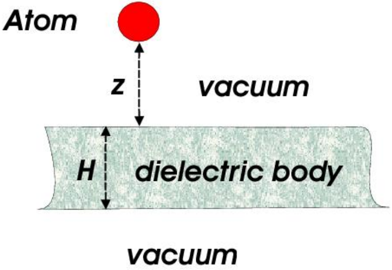
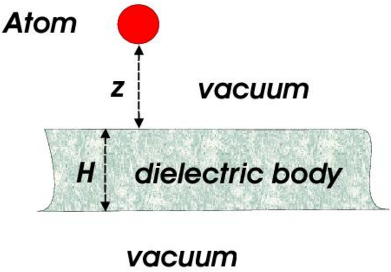
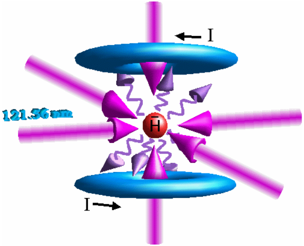
# Lifetime of an Atom Chip



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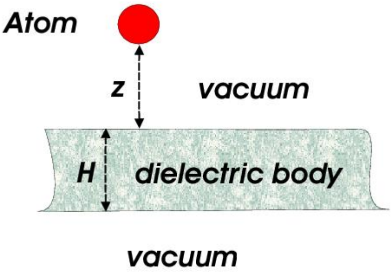
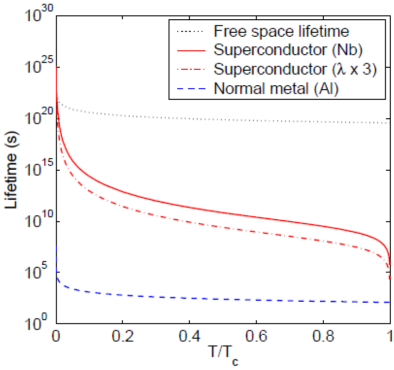
# Lifetime of an Atom Chip



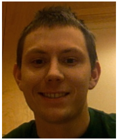



# Collaborators

Currently am I working with the following persons:

Prof. Bo-Sture Skagerstam,
NTNU / CAS Oslo / Gøteborg

Asle Heide Vaskinn, Ph. D. student, NTNU

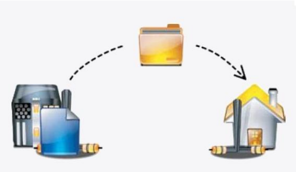


Arne Løhre Grimsmo, Ph. D. student,
University of Auckland, New Zealand

# Live in Molde

- video conferencing
- screen sharing
- FTP server in Molde:
  need good up- and download speed
- collaborators:
  Gøteborg / Oslo / Trondheim / New Zealand / England

**Video meetings**



FTP **server**

# Istad fiber

Solution: Istad fiber

# Research and development (R&D)

R&D:

- future-oriented, longer-term activities in science or technology
- using similar techniques to scientific research
- no predetermined outcomes
- with broad forecasts of commercial yield

USA:

- typical ratio of R&D: 3.5 % of revenues
- high technology company: ( computer manuf. ) 7 %

Germany:

- Siemens, 2011: 5.3 % of revenues ( 3.925 billion euro )

# Symphony of Science

[Morgan Freeman]
So, what are we really made of?
Dig deep inside the atom
and you'll find tiny particles
Held together by invisible forces

Everything is made up
Of tiny packets of energy
Born in cosmic furnaces

[Frank Close]
The atoms that we're made of have
Negatively charged electrons
Whirling around a big bulky nucleus

[Michio Kaku]
The Quantum Theory
Offers a very different explanation
Of our world

[Brian Cox]
The universe is made of
Twelve particles of matter
Four forces of nature

That's a wonderful and significant story

[Richard Feynman]
Suppose that little things
Behaved very differently
Than anything big

Nothing's really as it seems
It's so wonderfully different
Than anything big

The world is a dynamic mess
Of jiggling things
It's hard to believe


[Kaku]
The quantum theory
Is so strange and bizarre
Even Einstein couldn't get his head around it

[Cox]
In the quantum world
The world of particles
Nothing is certain
It's a world of probabilities

(refrain)

[Feynman]
It's very hard to imagine
All the crazy things
That things really are like

Electrons act like waves
No they don't exactly
They act like particles
No they don't exactly

[Stephen Hawking]
We need a theory of everything
Which is still just beyond our grasp
We need a theory of everything, perhaps
The ultimate triumph of science

(refrain)

[Feynman]
I gotta stop somewhere
I'll leave you something to imagine

Video: 08 Symphony, (3 min. 29 sec.)

# Summary


- Fundamental research
  - awareness of research and development
  - long term basis
- Example: Quantum optics
  - quantum computers
  - search more quickly
  - simulate molecules
  - quantum cryptography
- Istad fiber makes it possible with an international collaboration, living in Molde

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# Thank you

Thank you for the attention!