PQE-2011, SnowBird, Utah

Ben-Gurion University

Last year: 10th anniversary lecture
Someone asked me about QIP.

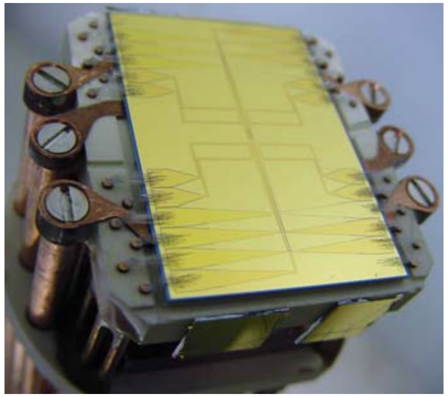
Engineering the Environment of Quantum Information Processing on AtomChips: Where Material Science meets Quantum Optics

Ron Folman

More information coming up in:

- new book on atom chips
  (Editors: Jakob Reichel and Vladan Vuletic)

- special issue on QIP
  (Journal of Quantum Information Processing
  Editors :Howard Brandt & RF)



Science 2008

Outline

- Brief intro to QIP
- Quick reminder of AtomChip
- Examples of our work on noise and materials

The city of Be'er Sheva (5000 years old): Capital of the Negev Desert (UNESCO world haritage site)

ויאמר כי את שבע כבשת תקח מידי בעבור תהיה
לי לעדה כי חפרתי את הבאר הזאת על כן קרא
למקום ההוא באר שבע כי שם נשבעו שניהם
ויכרתו ברית בבאר שבע ויקם אבימלך ופיכל
שר צבאו וישבו אל ארץ פלשתים ויטע אשל
בבאר שבע ויקרא שם בשם יהוה אל עולם ויגר
אברהם בארץ פלשתים ימים רבים

(Genesis, Ch. 21)

The ancient city of Be'er Sheva

The New York Times

Week in Review

SUNDAY, JUNE 10, 2007

Israel Discovers Oil

By THOMAS L. FRIEDMAN

BEERSHEBA, Israel

Lucien Bronicki is one of Israel's foremost experts in geothermal power, but when I ran into him last week at Ben Gurion University, in Israel's Negev Desert, all he wanted to talk about was oil wells. Israel, he told me, had discovered oil.

Pointing to a room full of young Israeli high-tech college seniors, Mr. Bronicki remarked: "These are our oil wells."

It was quite a scene. Once a year Ben Gurion students in biomedical engineering, software, electrical engineering and computing create elaborate displays of their senior projects or — as in the case of a student-made robot that sidled up to me — demonstrate devices they've invented.

On this occasion, Yossi Vardi, the godfather of Israeli venture capitalism — ever since he backed the four young Israelis who invented the first Internetwide instant messaging system, Mirabilis, which was sold to AOL for $400 million in 1998 — brought some of his venture capital pals, like Mr. Bronicki, down to Ben Gurion to scout out potential start-ups and to mentor the grads.

Tapping the power in imagination.

up," said Mr. Vardi, who is currently invested in 38 different ones.

Which gets to the point of this column: If you want to know why Israel's stock market and car sales are at record highs — while Israel's government is paralyzed by scandals and war with Hamas and doesn't even have a finance minister — it's because of this ecosystem of young innovation and connectivity empowering individuals from anywhere to compete, connect and collaborate — the most important competition is between you and your own imagination, because energetic, innovative and connected individuals can now act on their imaginations farther, faster, deeper and cheaper than ever before.

Those countries and companies that empower their individuals to imagine and act quickly on their imagination are going to thrive. So while there are reasons to be pessimistic about Israel these days, there is one huge reason for optimism: this country has a culture that nurtures and rewards individual imagination — one with no respect for limits or hierarchies, or fear of failure. It's a perfect fit with this era of globalization.

"We are not investing in products or business plans today, but in people who have the ability to imagine and connect dots," said Nimrod Kozlovski, a top Israeli expert on Internet law who also works with start-ups. Israel is not good at building big companies, he explained, but it is very good at producing people who say, "Wouldn't it be great if you could do this . . .," then create a start-up to do it — which is later bought out and expanded by an Intel, Microsoft or Google.

"The motto here is not work hard but dream hard," Mr. Kozlovski added. "I had some guy come see me the other day and say, 'You know Google? They make a lot of money, very famous, right? They're not that good. We have a much better system that correlates to the

A quick look at quantum computing:

The short DiVincenzo list for QIP (quant-ph/0002077, 2000):

- storage of the quantum information in a 2-level system (qubit)
- manipulating the state through 1-qubit operations
- processing the information using 2-qubit gates
- reading out the results
- long coherence times relative to the gate (‘clock‘) time (10^4!!!)

⟶ Decoherence (de-phasing), Zeh, Zurek, Aharonov, Henkel...

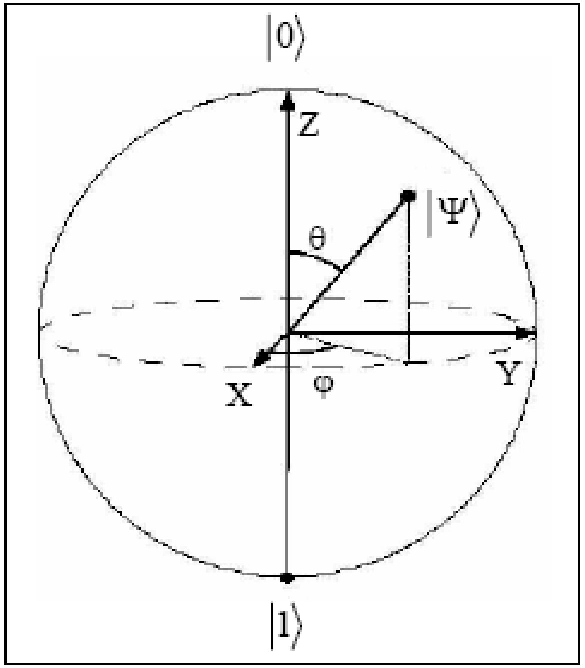
The tibetan monk....

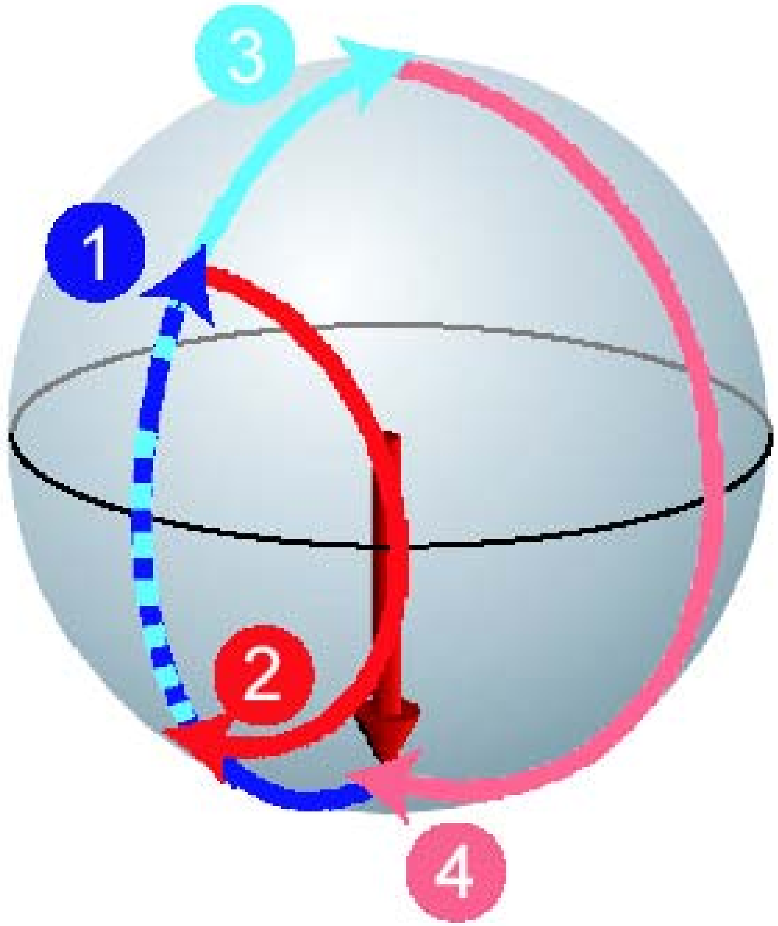
Solutions:

- realistic estimate of the coupling to noisy environment
- environment engineering
- non-destructive measurements
- error correction

Single qubit rotations:

$$|\Psi\rangle = \cos\frac{\theta}{2}|0\rangle + e^{i\varphi}\sin\frac{\theta}{2}|1\rangle$$





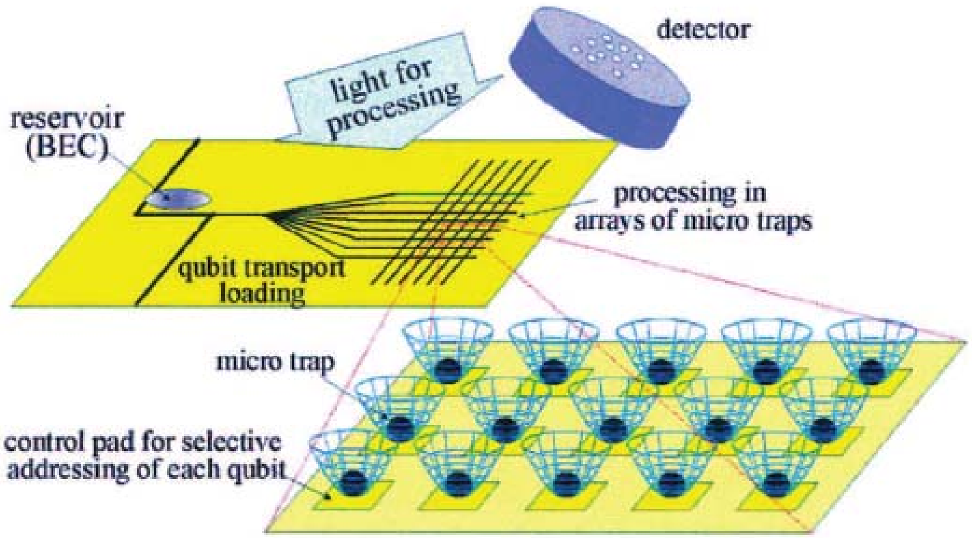
How to walk on the bloch sphere:
starting from the south pole
> 1. pulse area: pi/sqrt(2) , phase: 0
> 2. pi , pi/2
> 3. pi/sqrt(2), 0
> 4. pi, pi/2
ending in the south pole

Dark time between pulses does not matter!
As long as the 'zero phase' is counted properly
and there is no frequency error.
i.e. dark time (or pulse time for that matter)
cannot be bigger than 1/line width

Two qubit gates:

Example: CNOT truth table

Before		After	
Control	**Target**	**Control**	**Target**
0	0	0	0
0	1	0	1
1	0	1	1
1	1	1	0



Many possible realizations

Superconductor-based quantum computers
(including SQUID-based quantum computers)[17]
Trapped ion q
Optical lattices
Topological quantum c
Quantum dot on surfac … m computer)
Nuclear magnetic reso … d NMR)
Solid state NMR Kane
Electrons on helium qu
Cavity quantum electro
Molecular magnet
Fullerene-based ESR c
Optic-based quantum c
Diamond-based quantu
Bose–Einstein conden
Transistor-based quant … puters with
entrainment of positive
Spin-based quantum c
Adiabatic quantum computation[23]
Rare-earth-metal-ion-doped inorganic crystal based quantum computers[24][25]

An interesting question: is a quantum simulator an intermediate step?

Nature Physics **6**, 382 - 388 (2010)
Published online: 14 March 2010 | doi:10.1038/nphys1614

Subject Categories: Atomic and molecular physics | Quantum physics |

A Rydberg quantum simulator

Hendrik Weimer[1], Markus Müller[2], Igor Lesanovsky[2,3], Peter Zoller[2] & Hans Peter Büchler[1]

A universal quantum simulator is a controlled quantum device that reproduces the dynamics of any other many-particle quantum system with short-range interactions. This dynamics can refer to both coherent Hamiltonian and dissipative open-system evolution. Here we propose that laser-excited Rydberg atoms in large-spacing optical or magnetic lattices provide an efficient implementation of a universal quantum simulator for spin models involving *n*-body interactions, including such of higher order. This would allow the simulation of Hamiltonians of exotic spin models involving *n*-particle constraints, such as the Kitaev toric code, colour code and lattice gauge theories with spin-liquid phases. In addition, our approach provides the ingredients for dissipative preparation of entangled states based on engineering *n*-particle reservoir couplings. The basic building blocks of our architecture are efficient and high-fidelity *n*-qubit entangling gates using auxiliary Rydberg atoms, including a possible dissipative time step through optical pumping. This enables mimicking the time evolution of the system by a sequence of fast, parallel and high-fidelity *n*-particle coherent and dissipative Rydberg gates.

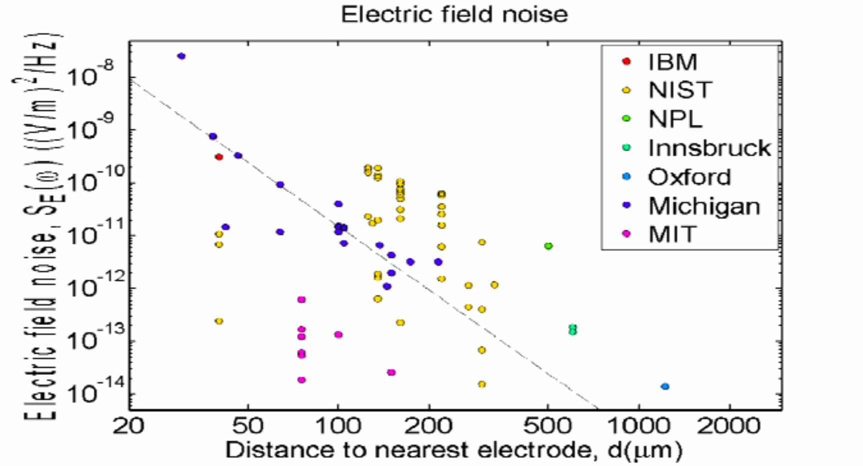

Welcome to D-Wave Systems - Mozilla Firefox
File Edit View History Bookmarks Tools Help
http://www.dwavesys.com/
Google
Most Visited
Getting Started
Latest Headlines
Timeline of quantum computing - Wikipe...
Welcome to D-Wave Systems
The Quantum Computing Company™
Company
Technology
Resources
Publications
Careers
Copyright © 2009 D-Wave Systems Inc. All rights reserved.
First look: "Rainier" silicon ready for testing and analysis.
WELCOME TO D-WAVE SYSTEMS
D-Wave is pioneering the development of a new class of high-performance computing system designed to solve complex search and optimization problems, with an initial emphasis on synthetic intelligence and machine learning applications.
D-Wave systems are architected around an innovative processor that uses a computational model known as adiabatic quantum computing (AQC). These processors exploit quantum effects to solve search and optimization
HIGHLIGHTS
D-Wave Blog
D-Wave founder and CTO Dr. Geordie Rose discusses D-Wave science and technology
Done
start
Aug2010
Inbox - Outloo...
Welcome to D-...
Microsoft Pow...
EN
01:08

Example of relevant parameters

Interesting (Tibetan Monk) question: how close can we get to a surface e.g. in ions, Anomalous Heating?

$$\langle \dot{n} \rangle = \frac{e}{4m\hbar\omega} S_E(\omega) \sim \frac{1}{d^4}$$

$S_E(\omega)$: spectral density of electric-field fluctuations



Courtesy of Dietrich Leibfried

<u>In ion traps:</u>

- best qubit coherence: 15s (Be+ in Paul trap)
- fastest two qubit gate: 7 µs (Be+ in Paul trap)
- fastest single qubit gate: few ps (Yb+ driven by pulsed laser)

<u>In atom traps:</u>

+ best qubit coherence on an atom chip @ a few µm: seconds (Treutlein, Reichel)
+ fastest two qubit gate demo 5µs (Rydberg, Saffman), expected 1ms (chip, Treutlein)
+ fastest planned two qubit gate 1ps (Optimal Control, Christiane Koch)

Warning: people typically use single qubit coherence times when they should use the coherence time of a N qubit entangled state

Coherence time goes down as 1/N-1/N^2

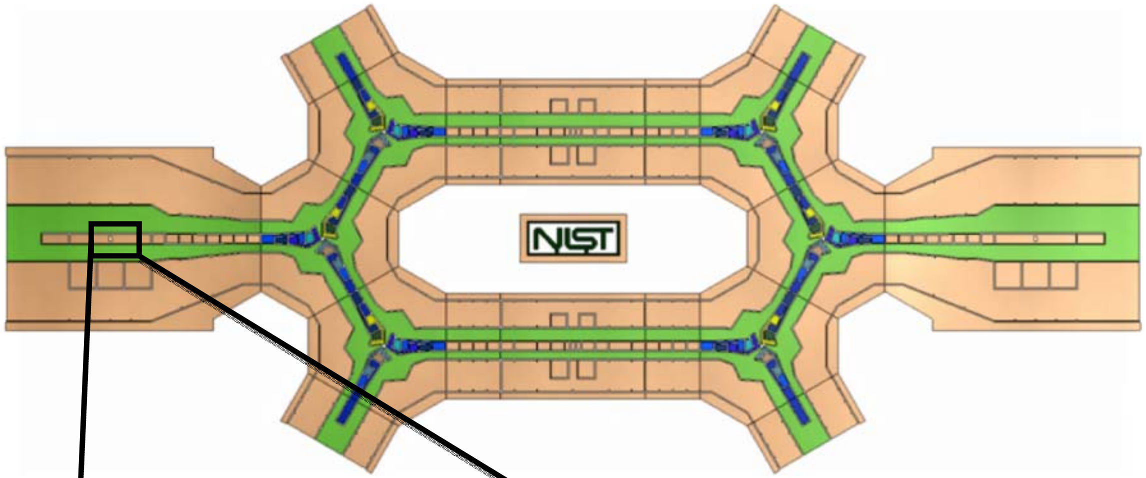
van Kampen, J. Stat. Phys. 78 (1995) 299
G.M. Palma et al., P. R. Soc. Lon. A 452 (1996) 567
B. J. Dalton, J. mod. Optics 50 (2003) 951
R. Doll et al., Europhys. Lett. 76 (2006) 547

Fidelity or infidelity is another important issue: from 0.1-10% (error correction/detection)
A. M. Steane, Phys. Rev. A 68, 042322(2003)
E. Knill, Phys. Rev. A 71, 042322 (2005).

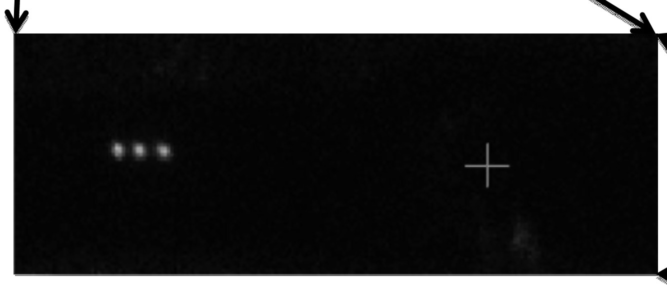
Another relevant parameter is scalability and mobility:

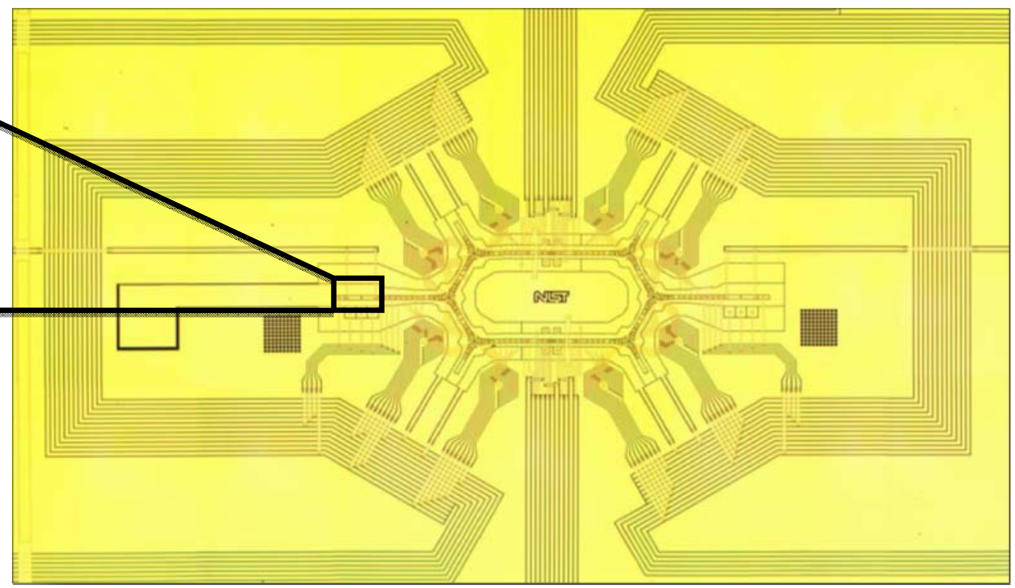
NIST ion trap chip module

(Jason Amini)

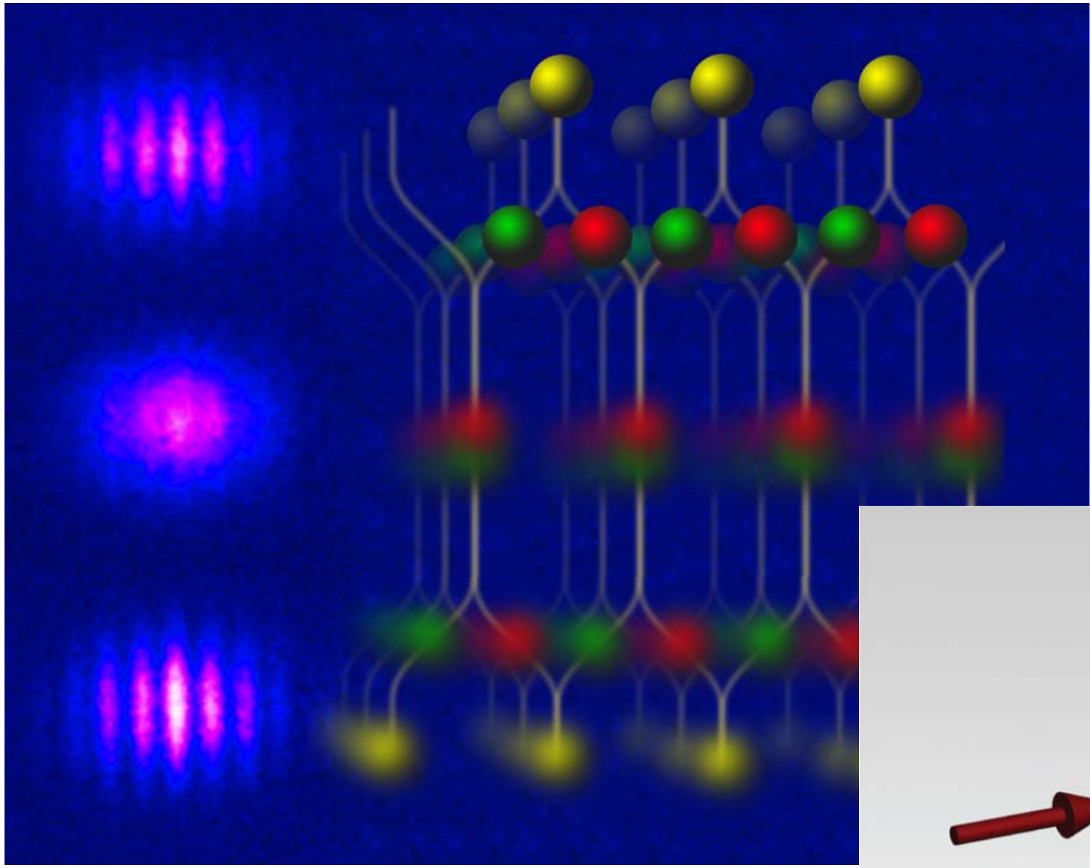


- 2 load zones
- 6 improved junctions
- 150 control electrodes



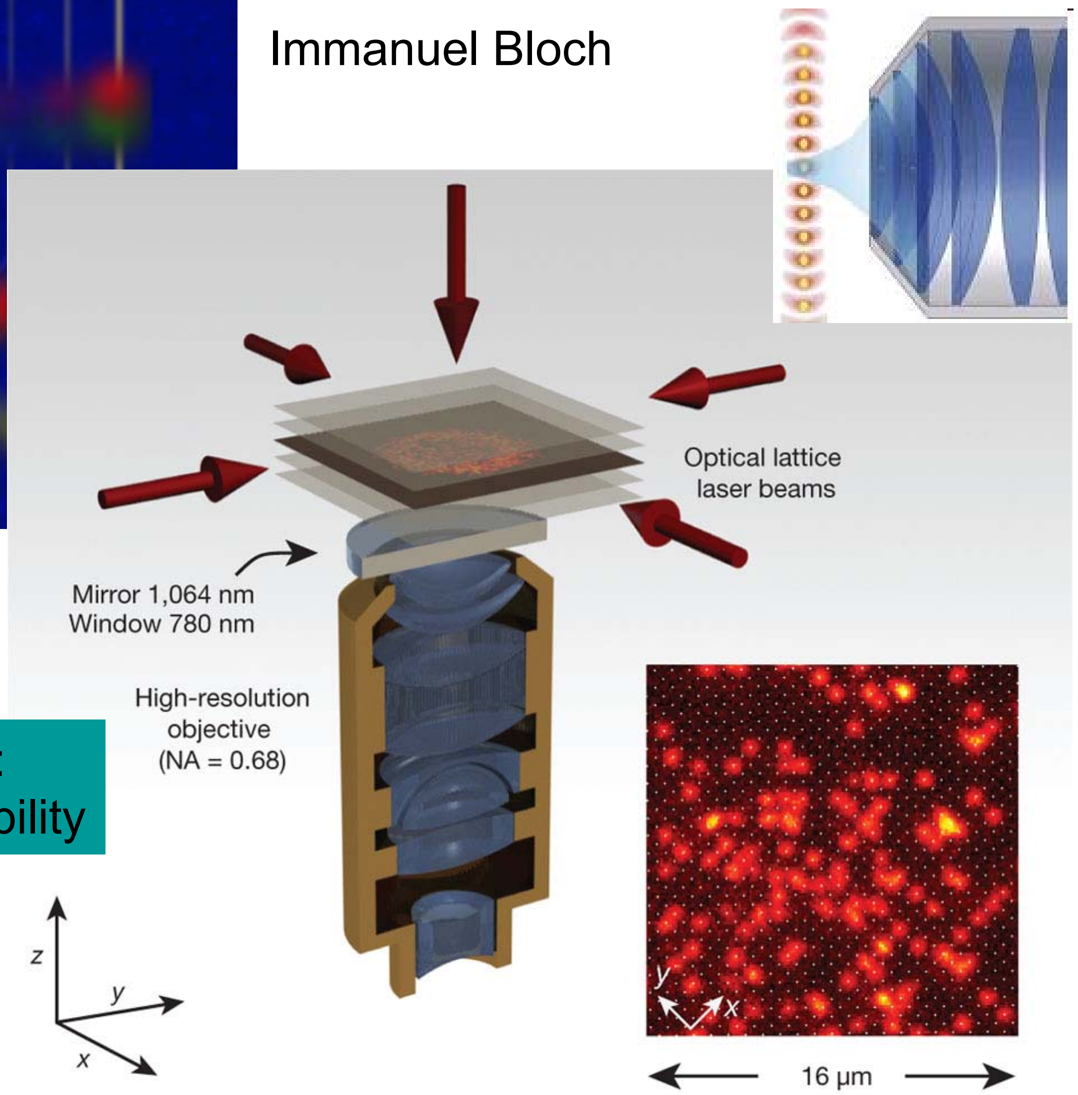


- backside loading
- motion through junctions
- utilize for multi-qubit work



Scalability with neutral atoms seems to be easier

Immanuel Bloch

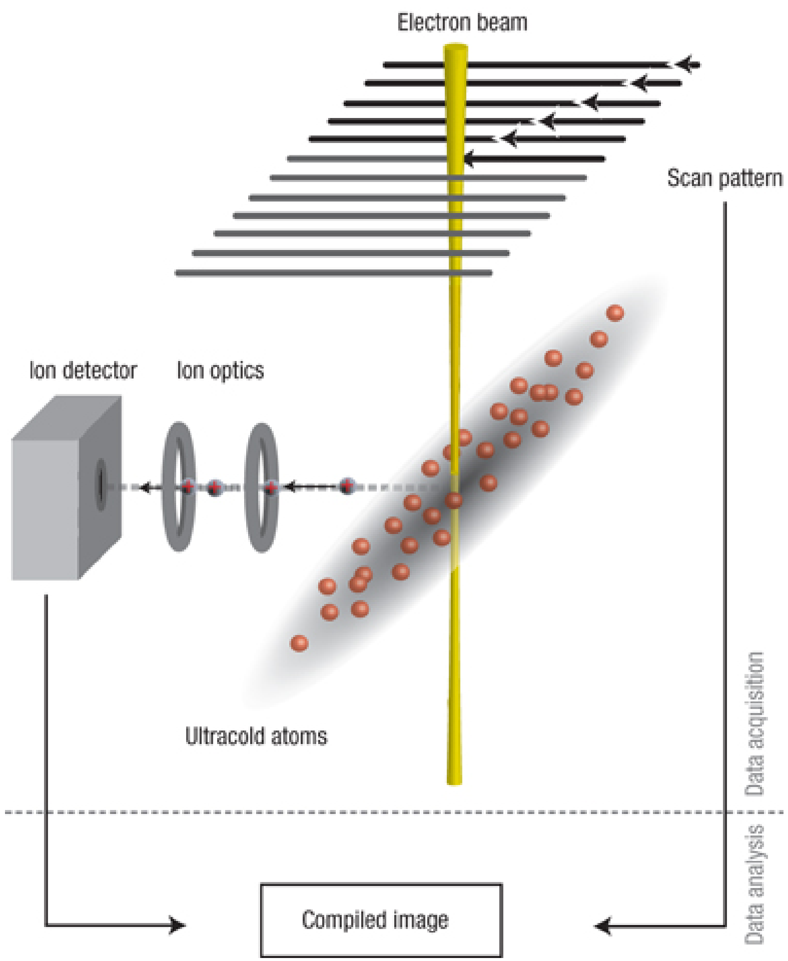


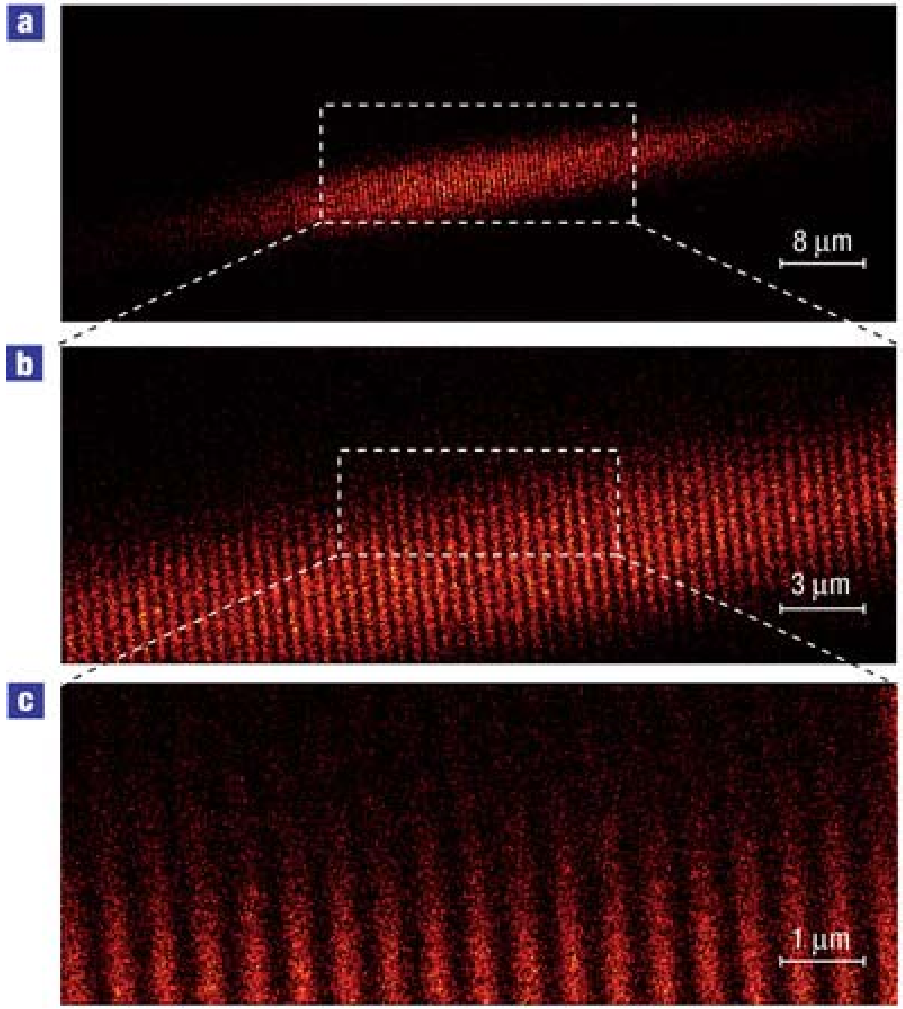
Two qubit rotation feasibility study via interferometry

One of the problems:
Single site addressability

One more beautiful view of single site addressability:

Herwig ott





Another problem: interaction strength

Possible solutions: combinations of atom-molecules-ryberg or mediating cannels

VOLUME 88, NUMBER 6 PHYSICAL REVIEW LETTERS 11 FEBRUARY 2002

Quantum Computation with Trapped Polar Molecules

D. DeMille

Department of Physics, P.O. Box 208120, Yale University, New Haven, Connecticut 06520

(Received 27 October 2001; published 24 January 2002)

We propose a novel physical realization of a quantum computer. The qubits are electric dipole moments of ultracold diatomic molecules, oriented along or against an external electric field. Individual molecules are held in a 1D trap array, with an electric field gradient allowing spectroscopic addressing of each site. Bits are coupled via the electric dipole-dipole interaction. Using technologies similar to those already demonstrated, this design can plausibly lead to a quantum computer with $\gtrsim 10^4$ qubits, which can perform $\sim 10^5$ CNOT gates in the anticipated decoherence time of ~ 5 s.

DOI: 10.1103/PhysRevLett.88.067901 PACS numbers: 03.67.Lx, 33.55.Be, 33.80.Ps

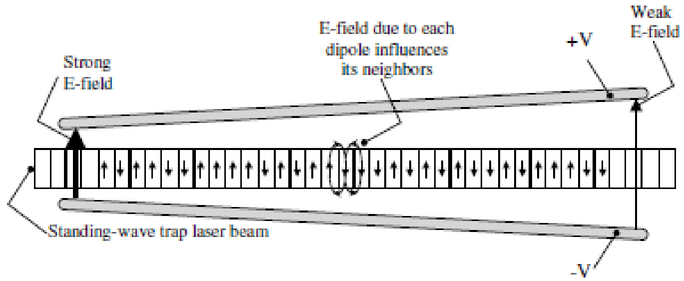


FIG. 1. Schematic depiction of the polar molecule quantum computer. Qubit states correspond to electric dipole moments up or down relative to the applied E-field.

PHYSICAL REVIEW A **81**, 030301(R) (2010)

Phase gate and readout with an atom-molecule hybrid platform

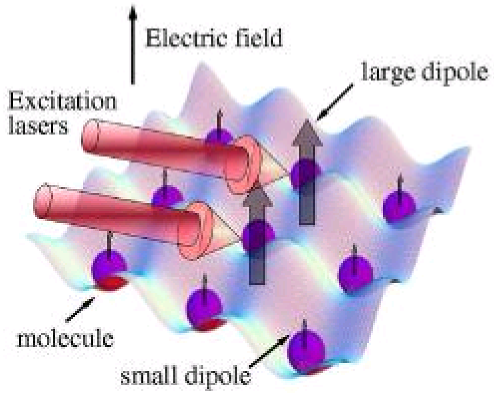
Elena Kuznetsova,[1,2] Marko Gacesa,[1] Susanne F. Yelin,[1,2] and Robin Côté[1]

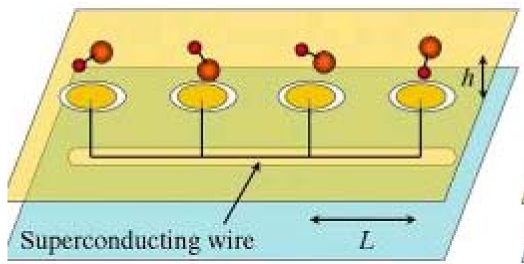
[1]*Department of Physics, University of Connecticut, Storrs, Connecticut 06269, USA*

[2]*ITAMP, Harvard-Smithsonian Center for Astrophysics, Cambridge, Massachusetts 02138, USA*

(Received 28 August 2009; published 4 March 2010)

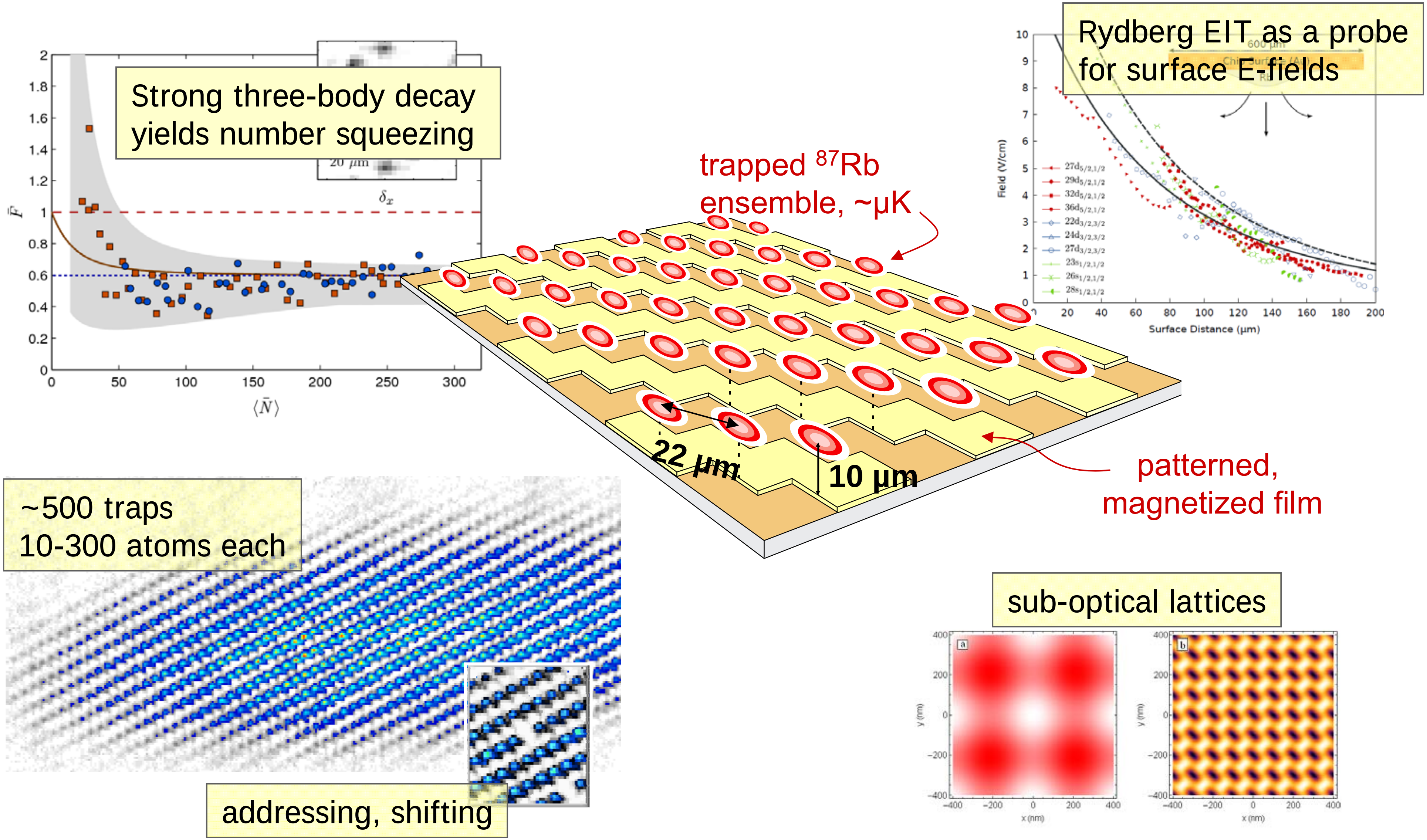
In order to optimize quantum information processing in individual traps such as optical lattices, we propose a combined atom-molecule system. In particular, gates, initialization, and readout are suggested, using two atoms of different species—one atom carrying the qubit and the other enabling interaction. We describe in some detail the implementation of a two-qubit phase gate in which a pair of atoms is transferred into the ground rovibrational state of a polar molecule with a large dipole moment, thus allowing molecules in adjacent sites to interact via their dipole-dipole interaction. We also discuss how the reverse process could be used as a nondestructive readout tool.





Some of what you can see in the QIP sessions

Microtrap arrays on magnetic film atom chip (R. Spreeuw)

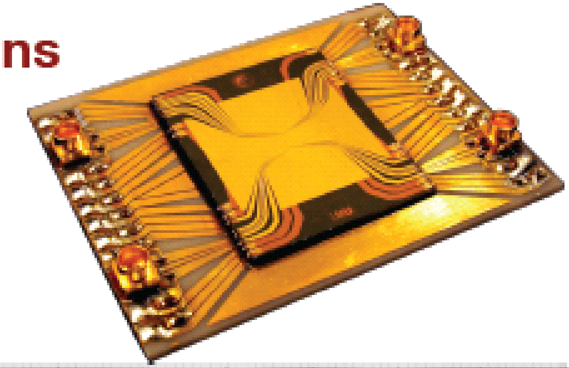


Multi-particle entanglement on an atom chip

Roman Schmied, Max F. Riedel, Pascal Böhi, and Philipp Treutlein

UNI BASEL

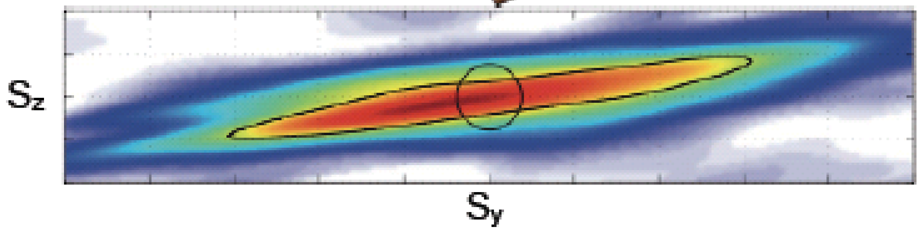
Entanglement in a BEC through controlled collisions



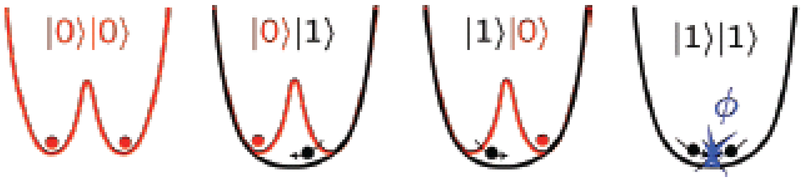
- Conditional dynamics in state-dependent microwave potential
- Useful spin-squeezing for quantum metrology
- Wigner function reconstructed from tomography data
- Experimental proof of entanglement

M. Riedel et al., Nature **464**, 1170 (2010).

P. Böhi et al., Nature Physics **5**, 592 (2009).

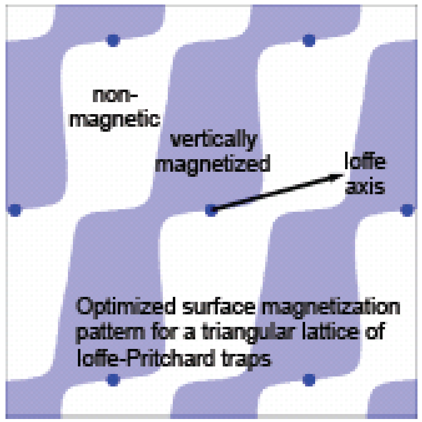


Towards quantum gates and quantum simulations



- Proposed collisional phase gate
- Predicted gate time: 1.1 ms, Fidelity: 99.6%

P. Treutlein et al., PRA **94**, 022312 (2006).

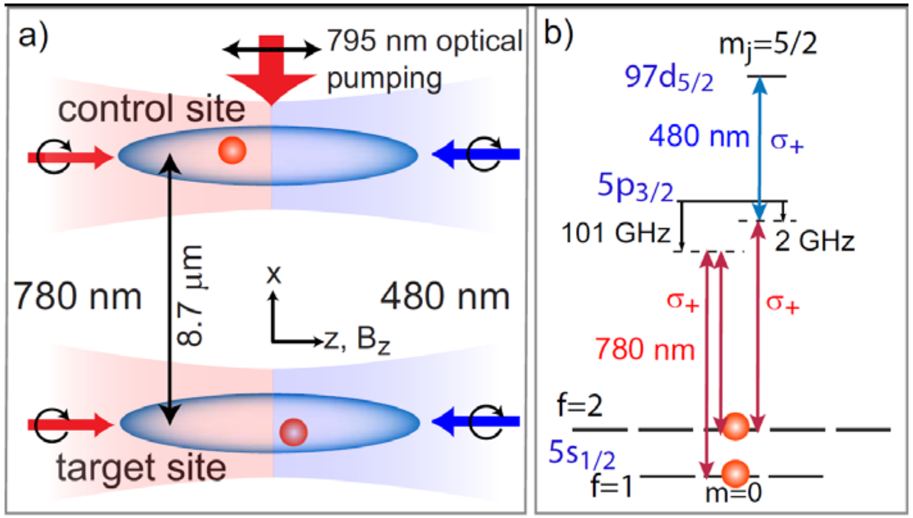


Optimal design of atom-chip structures for quantum simulation

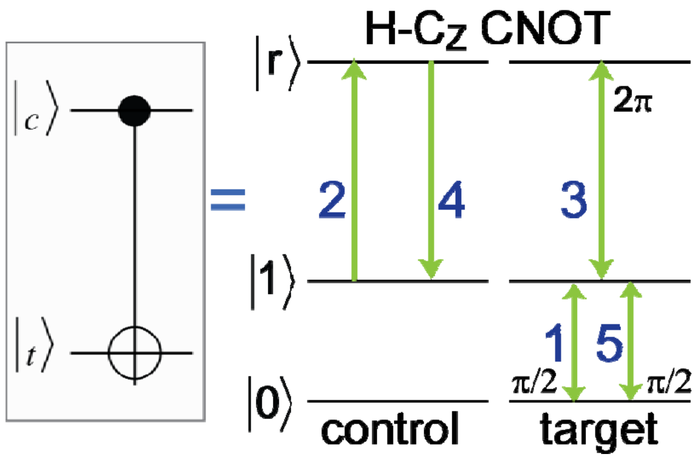
R. Schmied et al., New J. Phys. **12**, 103029 (2010).

A Neutral Atom CNOT Gate and Entanglement Using Rydberg Blockade (Xianli Zhang and Mark Saffman)

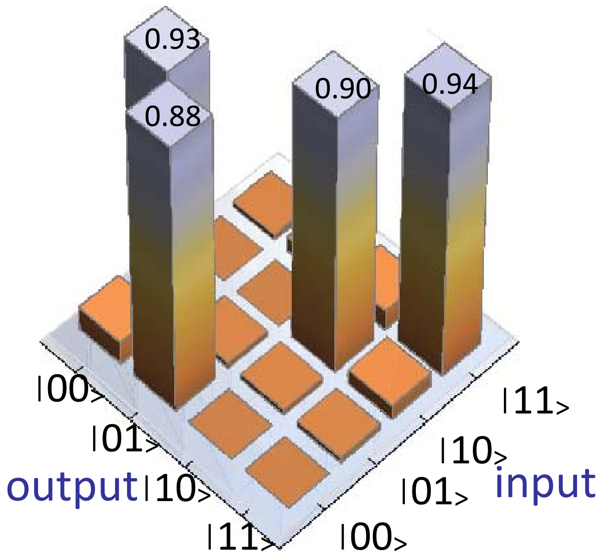
Experimental setup (^{87}Rb)



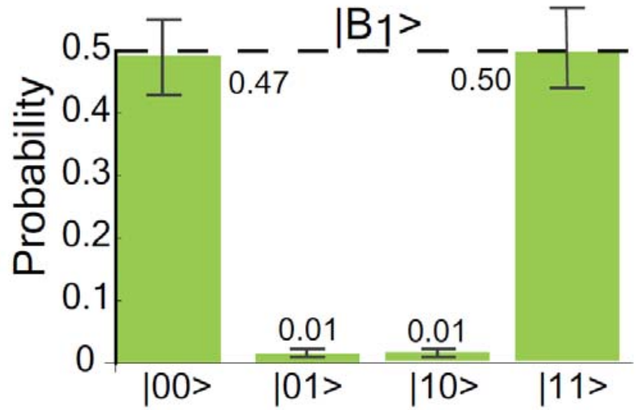
Two-qubit CNOT gate



$$\text{fidelity}: (1/4)Tr(U_{ideal}^{T}U_{\exp}) = .91$$



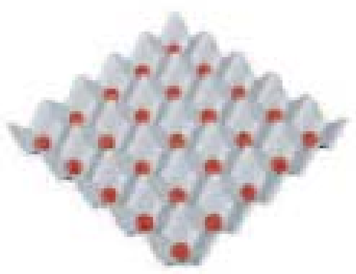
$$\text{Bell state}: (|00> + i|11>)/\sqrt{2}$$



L. Isenhower, et al. PRL 104, 010503 (2010)
X. L. Zhang, et al. PRA 82, 030306(R) (2010)

The problem of single atom loading:

Single atoms vs. ensembles



Optical lattices
(e.g. Immanuel Bloch)

New Journal of Physics
The open-access journal for physics

Scalable quantum computing with atomic ensembles

Sean D Barrett[1], Peter P Rohde[2] and Thomas M Stace[3,4]

Phys. Rev. Lett. 87, 037901 (2001)
Dipole Blockade and Quantum Information Processing in Mesoscopic Atomic Ensembles
M. D. Lukin, M. Fleischhauer, R. Cote, L.M. Duan, D. Jaksch, J.I. Cirac and P. Zoller

nature physics — LETTERS
PUBLISHED ONLINE: 26 SEPTEMBER 2010 | DOI:10.1038/NPHYS1778

Near-deterministic preparation of a single atom in an optical microtrap

T. Grünzweig, A. Hilliard, M. McGovern and M. F. Andersen*

Our work hypothesis

(=our vision)

What ever the eventual particle and interaction chosen,
chip technology will be required:

• fidelity demands will require accurate potentials,

• scalability will require repetitive architecture

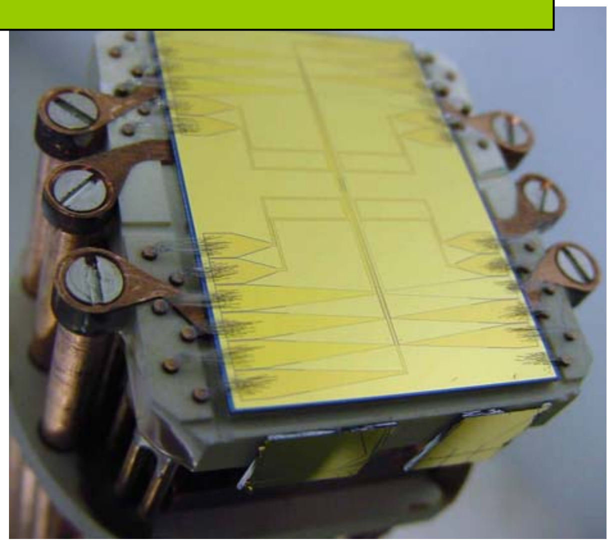
• short distance interactions will require high resolution architecture

• the need for different functions (vacuum, particle source, loading, control fields, detection, etc.) will require technology suitable for integration

• industry grade device will require robustness, small volume, low power consumption

With all this is mind.....

Engineering the Environment of Quantum Information Processing on AtomChips: Where Material Science meets Quantum Optics

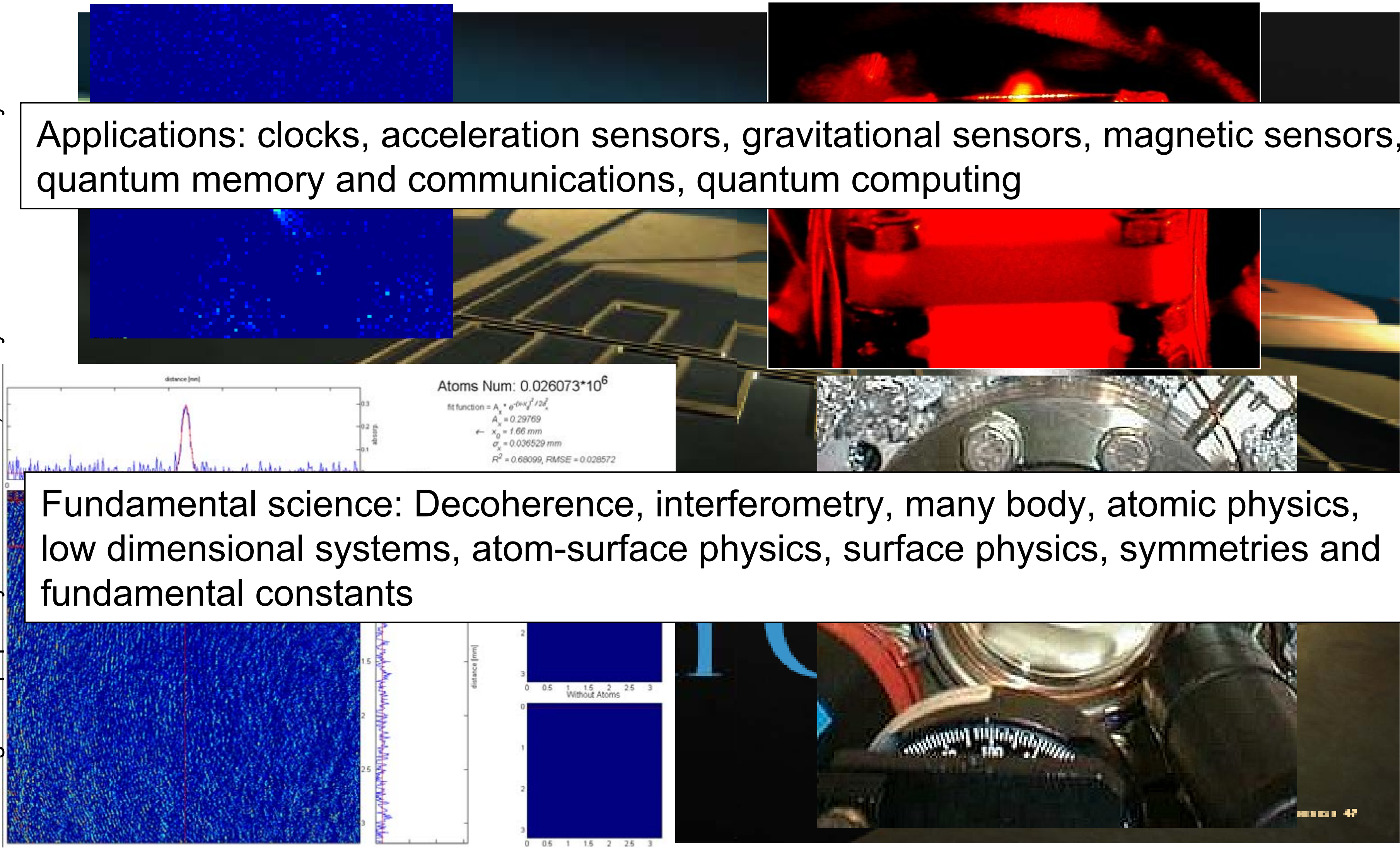


Atom Chip challenge:
To enhance functional environment
while suppressing harmful environment

A quick reminder of what the atom chip is:

One of the humble beginnings:
R. Folman et al.
Phys. Rev. Lett. 84, 4749 (2000)

Atom chip review article:
R. Folman et al.
Adv. At. Mol. Opt. Phys. 48, 263 (2002)



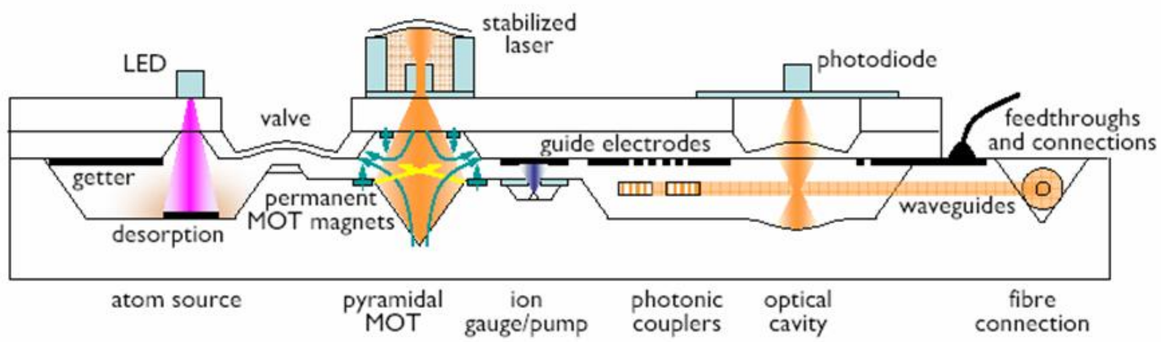
Applications: clocks, acceleration sensors, gravitational sensors, magnetic sensors, quantum memory and communications, quantum computing

Fundamental science: Decoherence, interferometry, many body, atomic physics, low dimensional systems, atom-surface physics, surface physics, symmetries and fundamental constants

Drawing from paper by Jakob Reichel; conveyer belt – invention by Ted Haensch

The monolithic integration dream

The atom chip technology is advancing very rapidly so that eventually, all the different realizations such as optical lattices, Rydberg, molecules, etc. may be put on the chip



Schematic diagram of an integrated atom chip with pumps, guides, MOT, integrated lasers and fibre connections.

Courtesy of Tim Freegarde

e.g. Dana Anderson (Monday talk by Evan Salim)

Some awkward uses of the AtomChip name

A real atom chip company


ColdQuanta: Cold Quanta, Ultracold Atom and BEC Devices, Instruments, Atom Optics and Systems - Mozilla Firefox

http://www.coldquanta.com/

ColdQuanta

COLDQUANTA HOME | COLDQUANTA PEOPLE | ULTRACOLD PRODUCTS | BOSE-EINSTEIN SCIENCE | PARTNERSHIPS | LINKS | NEWS | CAREERS | CONTACT

ColdQuanta's™ mission is to focus on the development of BEC generating devices and systems, allowing them to be accessible to a wide range of research, educational, and industrial institutions. Our products are intended for use in scientific and industrial applications requiring high performance and reliability. Our commitment to quality and customer satisfaction is paramount to us.

The release of the **RuBECi™**, the world's first commercial product designed to facilitate the creation of Bose Einstein condensates and ultra-cold matter in the laboratory setting creates exciting opportunities for researchers and applicators wishing to develop further the strides made in Atomic, Molecular and Optical (AMO) physics over the last two decades.

ECS - Developing atom chip devices to bring quantum computing closer - Mozilla Firefox

File Edit View History Bookmarks Tools Help

http://www.ecs.soton.ac.uk/about/news/1231

Most Visited | Getting Started | Latest Headlines

ECS - Developing atom chip devices to bring quantum computing closer

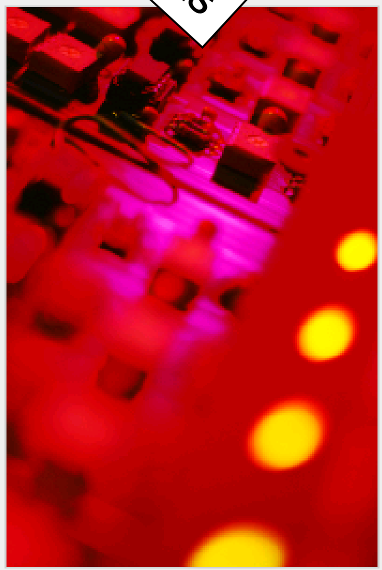
UNIVERSITY OF Southampton
School of Electronics and Computer Science

Home | UG Study | MSc Admissions | PG Opportunities | Research | People | Alumni | Contact | Intranet

University of Southampton > ECS > News > **Developing atom chip devices to bring quantum computing closer**

Relevant grants

Developing atom chip devices to bring quantum computing closer



A grant awarded this month could develop atom chip devices which could bring quantum computing closer to a reality.

Dr Michael Kraft at the University of Southampton's School of Electronics & Computer Science (ECS) and Professor Edward Hinds at Imperial College, London, have been awarded a £1.2 million Basic Technology Translation Grant from the Engineering and Physical Sciences Research Council (EPSRC) to develop atom chip devices.

Their task is to take the toolbox of basic atom chip building blocks which they have developed over the past four years and integrate them on a single chip so that they can be developed into systems robust enough to perform useful functions.

The researchers have found that atom chips have potential uses in a variety of futuristic technologies. For example: sensors with unprecedented accuracy and sensitivity; quantum computing, which harnesses physical phenomenon unique to quantum mechanics to realise a new mode of information processing, and atom interferometers, instruments that exploit the wave characters of atoms.

Specific atom chip devices to be explored in this new research include atomic clocks, accelerometers, interferometers, magnetometers, single photon sources, quantum information processors and molecule traps.

'Over the past four years, we have done the fundamental research into atom chips,' said Dr Kraft. 'Now it's time to make application-orientated devices.'

According to Dr Kraft, although other international research groups have worked on atom chips, there are not yet any atom chip devices. He believes that this is a development which will be of benefit to industry and the wider community in the longer term.

'There is a growing need for unprecedented accuracy in accelerometers and gyroscopes,' he said. 'Quantum information processors are potentially leading to quantum computers and atom chip devices will facilitate this process.'

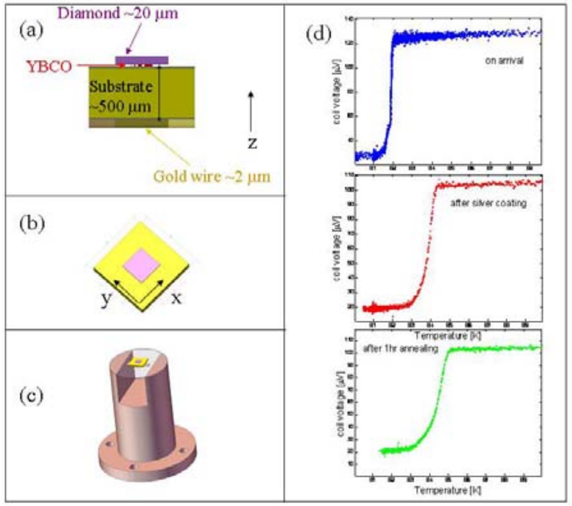
Done

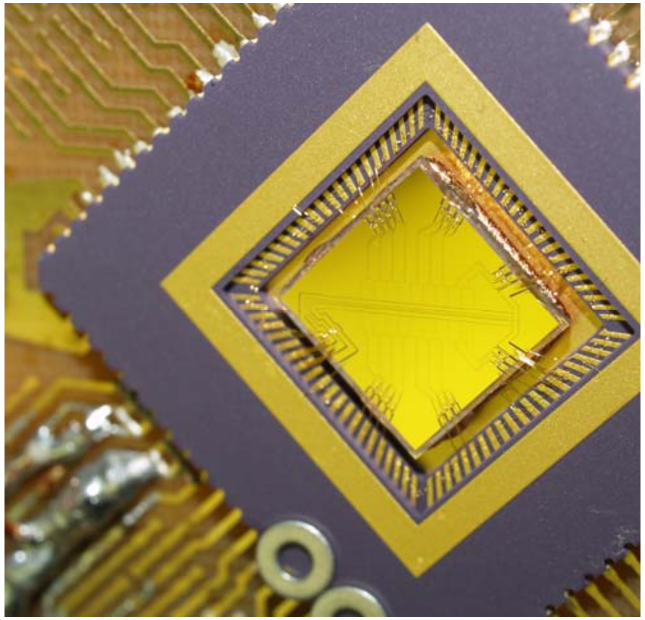
With this vision in mind,
at BGU we built a fabrication facility dedicated to the atom chip,

Expanding to different quantum systems, e.g.:
neutral atoms, ions, electrons, photons, molecules, NV centers.

Services to labs around the world:

Diamond Chip produced for Berkeley

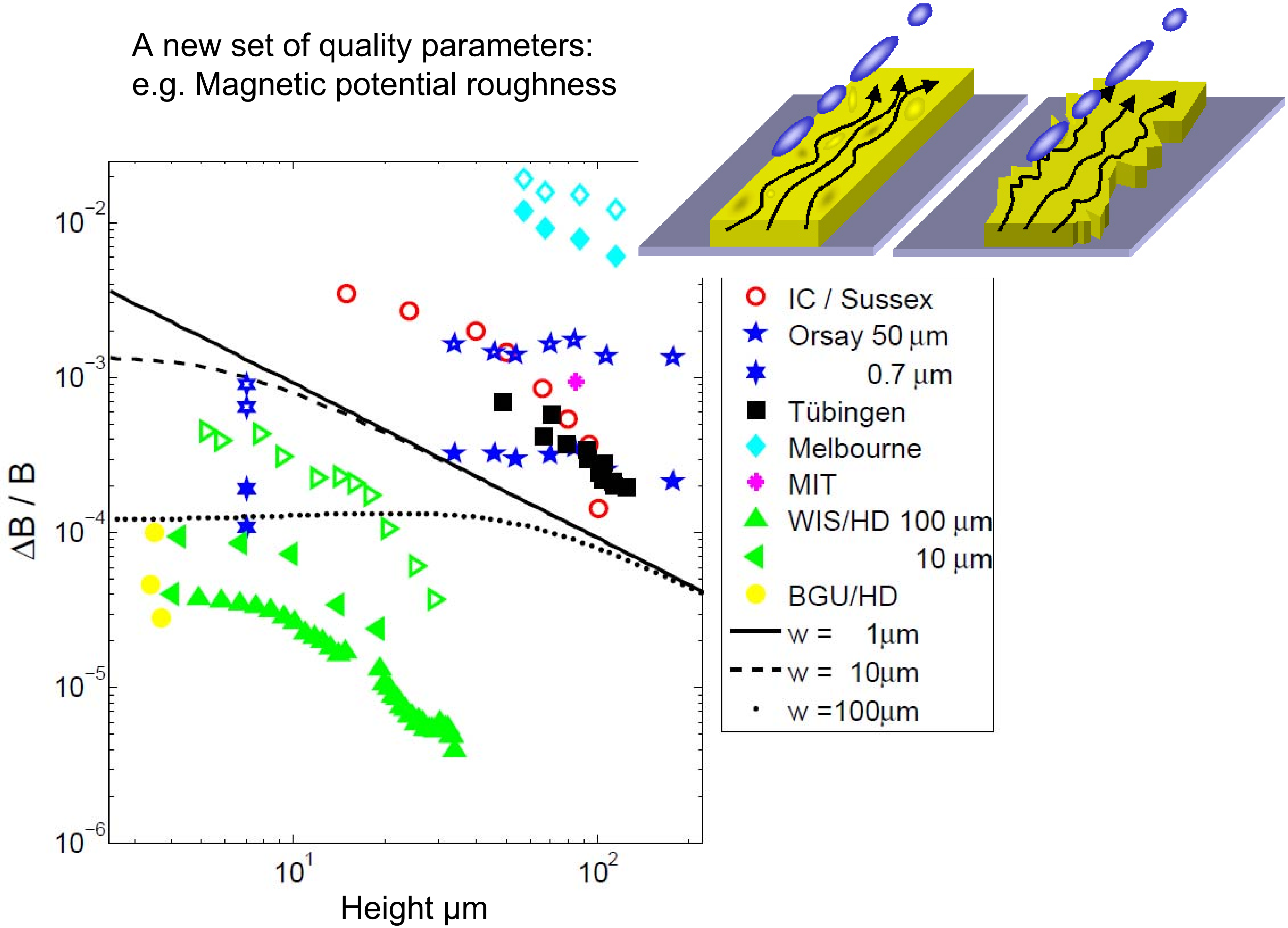




Ion Chip produced for Mainz

Atom Chips produced for Florence and Nottingham

A new set of quality parameters:
e.g. Magnetic potential roughness



Fabrication effort deals not only with electrodes: e.g. integrated photonics

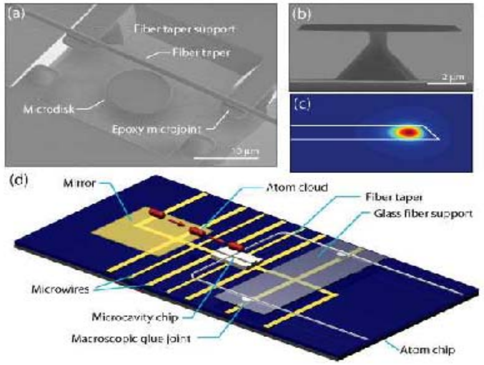
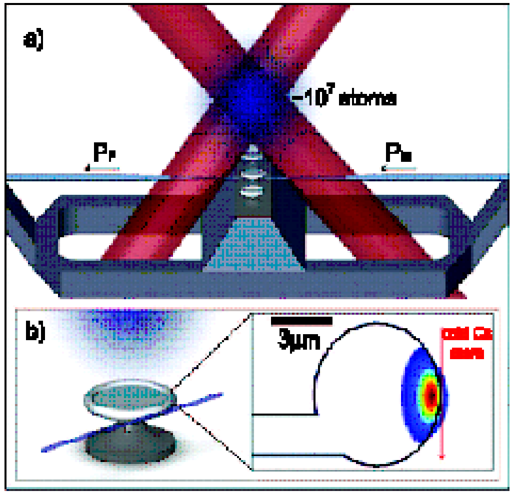
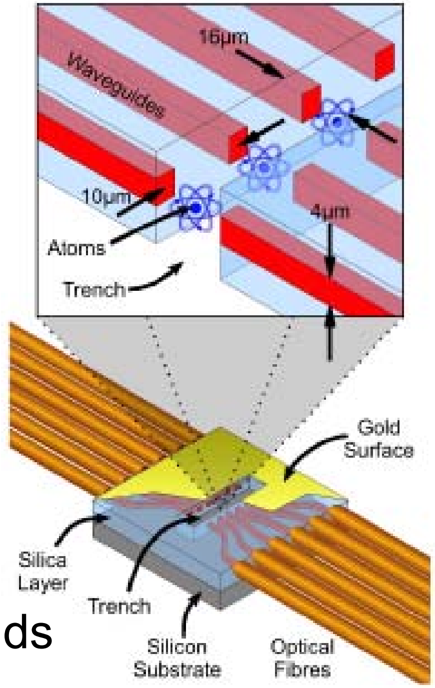


FIG. 1: (a) Scanning electron microscope (SEM) image of a SiN_x cavity coupled to an optical fiber taper. The fiber taper is permanently aligned a few hundred nanometers from the microdisk circumference with epoxy microjoints to SiN_x supports. (b) Side-view SEM image of a 9 μm diameter mircodisk. (c) FEM calculated field distribution ($|E|^2$) of a $m = 50$, $p = 1$, TE-like mode of the microdisk in (b). (d) Schematic of the integrated hybrid atom-cavity chip.

Hideo Mabuchi



Jeff Kimble



Ed Hinds

Photonics also for QIP:

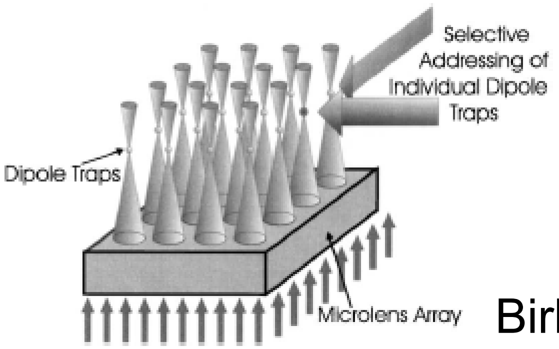
Decoherence, Continuous Observation, and Quantum Computing: A Cavity QED Model

Pellizzari, T., Gardiner, S.A., Cirac J. I. and Zoller, P.

Phys. Rev. Lett. **75**, 3788 (1995).

Our work:

- Phys. Rev. A 70, 053808 (2004)
- Phys. Rev. A 73, 063805 (2006)
- J. Nanophoton. 1, 011670 (2007)
- US patent: 7,466,889B1 (2008)



Birkl, Ertmer

Towards quantum computing with single atoms and optical cavities on atom chips

M. Trupke,[1] J. Metz,[1] A. Beige,[2] and E. A. Hinds[1]

[1]Blackett Laboratory, Imperial College London, Prince Consort Road, London SW7 2BZ, United Kingdom
[2]The School of Physics and Astronomy, University of Leeds, Leeds LS2 9JT, United Kingdom

February 1, 2008

Final example of the promise of AC photonics

Fabry-Perot for atoms

PHYSICAL REVIEW A VOLUME 47, NUMBER 3 MARCH 1993

Fabry-Pérot interferometer for atoms

M. Wilkens, E. Goldstein, B. Taylor, and P. Meystre
Optical Sciences Center, University of Arizona, Tucson, Arizona 85721
(Received 5 June 1992; revised manuscript received 20 October 1992)

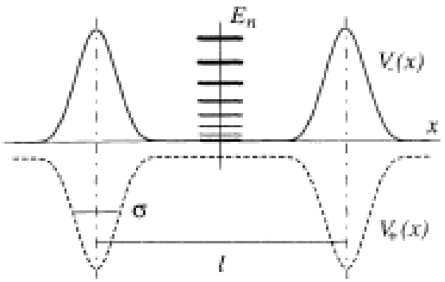


FIG. 1. Possible geometry of a Fabry-Pérot device for atoms, illustrating the potentials V_+ and V_- due to the optical fields, and sketching the resonant modes for the dressed state $|-\rangle$.

Can we make curved light mirrors?
With what corrugation?
Dispersion of mirrors?
Is there importance to deBroglie length vs. cavity length?
How would atom-atom collisions enter?
How do we load?
What beam will come out?

The place where the chip has the most advantage is single site addressability, near field, high gradients, low power consumption and interfaces (hybrid QIP)

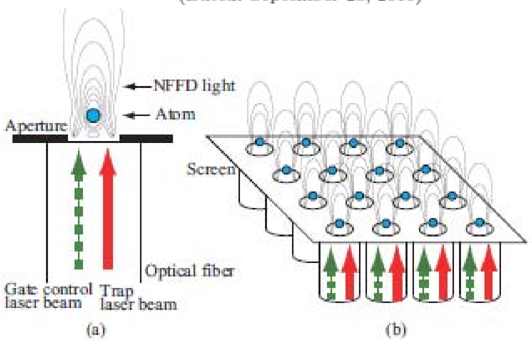
Scalable Neutral Atom Quantum Computer with Interaction on Demand

Mikio Nakahara*
Research Center for Quantum Computing, Interdisciplinary Graduate School of Science and Engineering, Kinki University, 3-4-1 Kowakae, Higashi-Osaka, 577-8502, Japan and Department of Physics, Kinki University, 3-4-1 Kowakae, Higashi-Osaka, 577-8502, Japan

Tetsuo Ohmi†
Research Center for Quantum Computing, Interdisciplinary Graduate School of Science and Engineering, Kinki University, 3-4-1 Kowakae, Higashi-Osaka, 577-8502, Japan

Yasushi Kondo‡
Research Center for Quantum Computing, Interdisciplinary Graduate School of Science and Engineering, Kinki University, 3-4-1 Kowakae, Higashi-Osaka, 577-8502, Japan Department of Physics, Kinki University, 3-4-1 Kowakae, Higashi-Osaka, 577-8502, Japan and

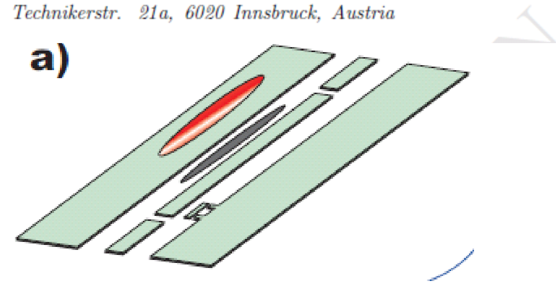
(Dated: September 23, 2010)



Strong magnetic coupling of an ultracold gas to a superconducting waveguide cavity

J. Verdú,[1] H. Zoubi,[2] Ch. Koller,[1] J. Majer,[1] H. Ritsch,[2] and J. Schmiedmayer[1]

[1] *Atominstitut der Österreichischen Universitäten, TU-Wien, 1020 Vienna, Austria*
[2] *Institut für Theoretische Physik, Universität Innsbruck, Technikerstr. 21a, 6020 Innsbruck, Austria*



Natural and artificial atoms for quantum computation

Iulia Buluta[1], Sahel Ashhab[1,2], and Franco Nori[1,2]
1 Advanced Science Institute, RIKEN, Wako-shi, Saitama, 351-0198, Japan
2 Department of Physics and Center for Theoretical Physics, The University of Michigan, Ann Arbor, Michigan 48109-1040, USA

(Dated: February 15, 2010)

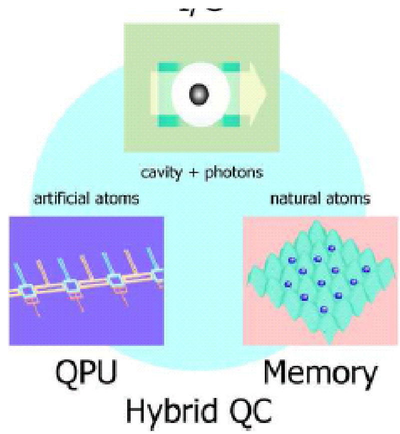
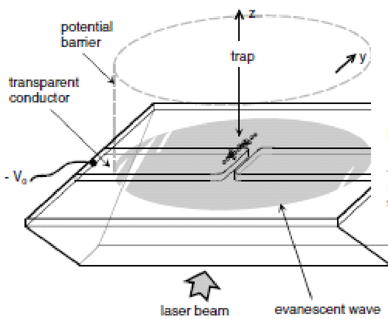


FIG. 1: Schematic representation of a hybrid device consisting of natural atoms as quantum memory, artificial atoms as "quantum processing unit" (QPU), and an input/output (I/O) photonic interface.

Evanescent fields



prism

Eur. Phys. J. D **28**, 273–276 (2004)
DOI: 10.1140/epjd/e2003-00309-0

THE EUROPEAN PHYSICAL JOURNAL D

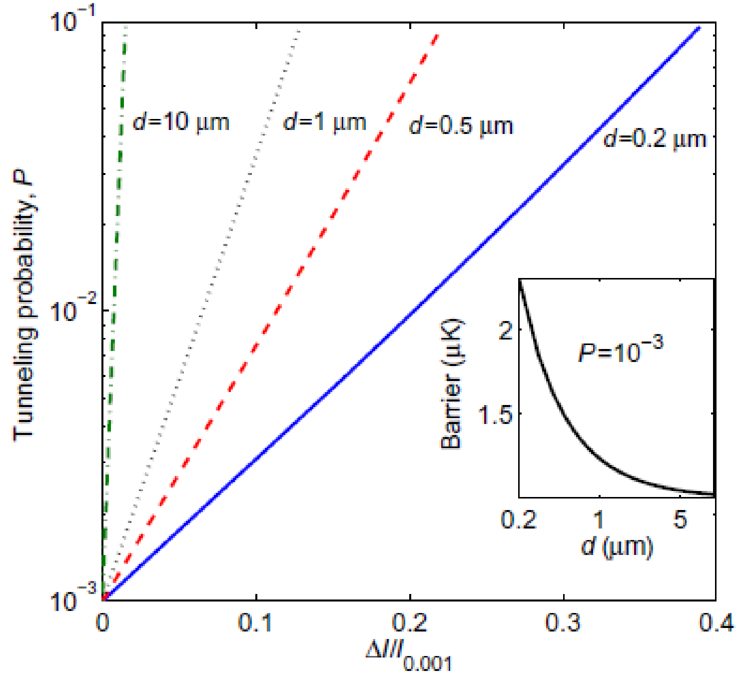
Microscopic electro-optical atom trap on an evanescent-wave mirror

A. Shevchenko[1,a], T. Lindvall[2], I. Tittonen[2], and M. Kaivola[1]

[1] Department of Engineering Physics and Mathematics, Helsinki University of Technology, P.O. Box 2200, 02015 HUT, Finland
[2] Metrology Research Institute, Helsinki University of Technology, P.O. Box 3000, 02015 HUT, Finland

Example of how being close to the surface helps:

Higher gradients mean more tunneling stability and thus enable lower infidelity in double well 2-qubit gates.



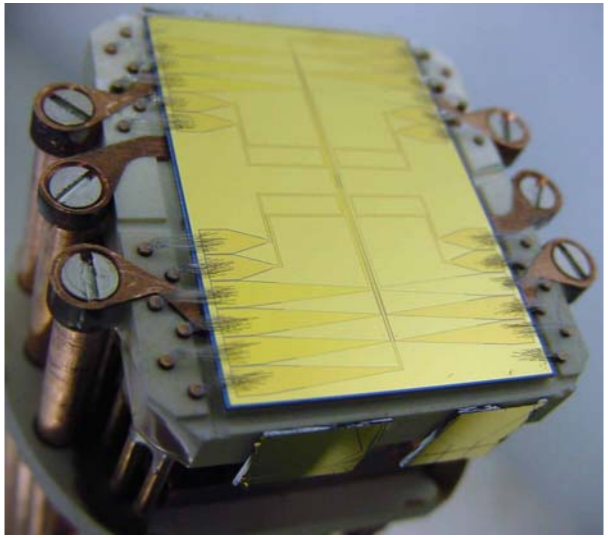
New Journal of Physics

The open-access journal for physics

(2010)

Nanowire atomchip traps for sub-micron atom–surface distances

R Salem[1,4], Y Japha[1], J Chabé[1], B Hadad[2], M Keil[1], K A Milton[3] and R Folman[1]



Atom Chip challenge:
To enhance functional environment
while suppressing harmful environment

► functional environment
The QIP environment will require for preparation, quantum control and measurement:
MEMs, photonics (incl. high finesse cavities), electronics, permanent magnets,
metal (current, charge, RF, MW), light and particle sources, light and particle detectors…
(I talked about some of these last year)

► harmful environment
But what about stability, fluctuation, corrugation, and isolation?
Remember for example the demand for 10^4 operations within
the coherence time.

In the rest of the talk I will focus on noise
(isolation)

Noise

Quite a few people working on the theory and experiment of noise

e.g.

Thermally induced spin flips above an atom chip

M. P. A. Jones, C. J. Vale, D. Sahagun, B. V. Hall and E. A. Hinds*
Blackett Laboratory, Imperial College, London SW7 2BW, United Kingdom
(Dated: December 15, 2009)

Impact of the Casimir-Polder Potential and Johnson Noise on Bose-Einstein Condensate Stability near Surfaces

Yu-ju Lin, Igor Teper, Cheng Chin, and Vladan Vuletić
*Department of Physics, Stanford University, Stanford, California 94305-4060**

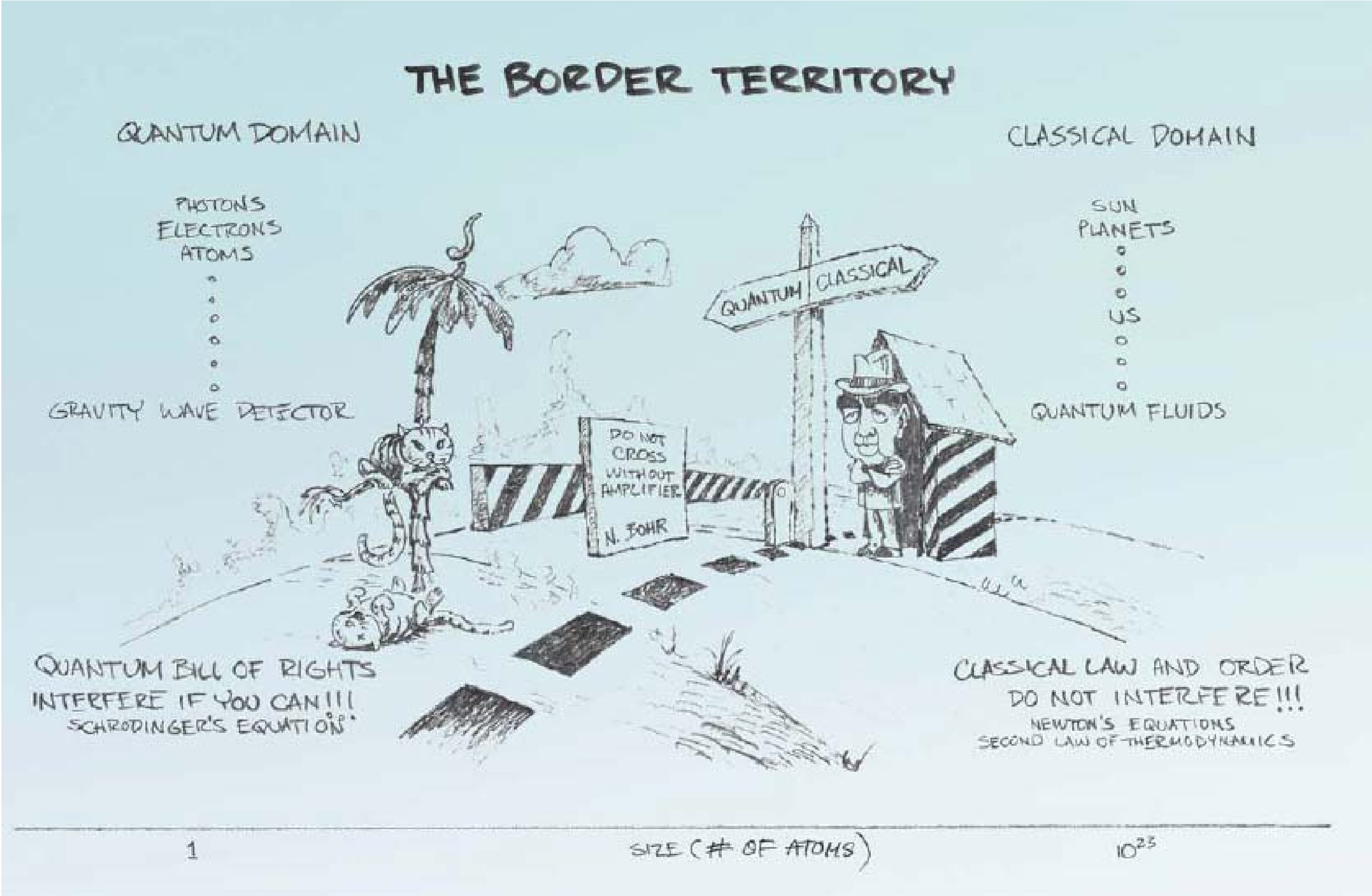
Measurement of the trapping lifetime close to a cold metallic surface on a cryogenic atom-chip

A. Emmert[1,a], A. Lupaşcu[1], G. Nogues[1,b], M. Brune[1], J.-M. Raimond[1], and S. Haroche[1,2]

[1] Laboratoire Kastler Brossel, ENS, CNRS, UPMC, 24 rue Lhomond, 75231 Paris Cedex 05, France
[2] Collège de France, 11 place Marcelin Berthelot, 75231 Paris Cedex 05, France

But why am I so interested in noise?
(its not just because it's a technological requirement)

Zurek
1991



On the fundamental front:
Its no longer only about size but about interaction strength and type that will determine how fast something will decohere and into what pointer basis.

The atom chip is a very suitable system for more insight as the surface is by far the most dominant environment,
it is a versatile environment and it is well controlled

SpringerLink - Foundations of Physics Letters, Volume 7, Number 2 - Mozilla Firefox

http://www.springerlink.com/content/8w11673j76558347/

One may think about this border from many different angles. e.g. outside QM (here, revisiting an old Bohm-Bub model)

Foundations of Physics Letters, Vol. 7, No. 2, 1994

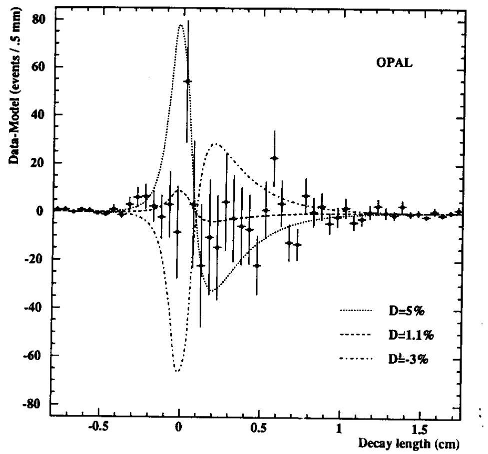
A SEARCH FOR HIDDEN VARIABLES IN THE DOMAIN OF HIGH ENERGY PHYSICS

Ron Folman

Physics Department
Weizmann Institute of Science
Rehovot, Israel

Received June 16, 1993; revised January 11, 1994

The idea of hidden variable theories, which contests the notion of quantum mechanics being the fundamental principle of nature, is well known and seems to need no introduction. In 1966 such a theory (of a non-local character) was proposed by D. Bohm and J. Bub. We present a scheme in which measured decay processes may constitute an adequate substitute to the original test proposed in 1966 and which until now proved to be realizable only for massless particles.



Physics Letters B, Volume 368, Issue 3, 1 February 1996, Pages 244-250

Test of the exponential decay law at short decay times using tau leptons

Over the years, in fact since quantum concepts began dominating over our classical notions, there have been numerous attempts

Done

start SpringerLink - Founda... EN 19:39

Or within QM, an effort to understand coherence:

PHYSICAL REVIEW A 70, 023810 (2004)

Optical discrimination between spatial decoherence and thermalization of a massive object

C. Henkel,[1] M. Nest,[2] P. Domokos,[3] and R. Folman[4]
[1]*Universität Potsdam, Institut für Physik, Am Neuen Palais 10, D-14469 Potsdam, Germany*
[2]*Universität Potsdam, Institut für Chemie, Karl-Liebknecht-Str. 25, D-14476 Potsdam, Germany*
[3]*Research Institute for Solid State Physics and Optics, Budapest, Hungary*
[4]*Department of Physics and Ilse Katz Center for Meso- and Nanoscale Science and Technology, Ben Gurion University of the Negev, P.O.Box 653, Beer Sheva 84105, Israel*
(Received 29 March 2004; published 23 August 2004)

PRL 96, 173601 (2006) PHYSICAL REVIEW LETTERS week ending 5 MAY 2006

Interference Swapping in Scattering from a Nonlocal Quantum Target

Daniel Rohrlich, Yakov Neiman, Yonathan Japha, and Ron Folman
Department of Physics, Ben-Gurion University, Beer-Sheva 84105, Israel
(Received 23 January 2006; published 5 May 2006)

We describe a new and distinctive interferometry in which a probe particle scatters off a *superposition* of locations of a *single* free target particle. Probe particles scattering off a single free "mirror" (in one dimension) or a single free "slit" (in two dimensions) can "swap" interference with the superposed target states. The condition for interference is *loss* of orthogonality of the target states and reduces, in simple examples, to *transfer* of orthogonality from target to probe states. We analyze experimental parameters and conditions necessary for interference to be observed.

PRL 99, 060402 (2007) PHYSICAL REVIEW LETTERS week ending 10 AUGUST 2007

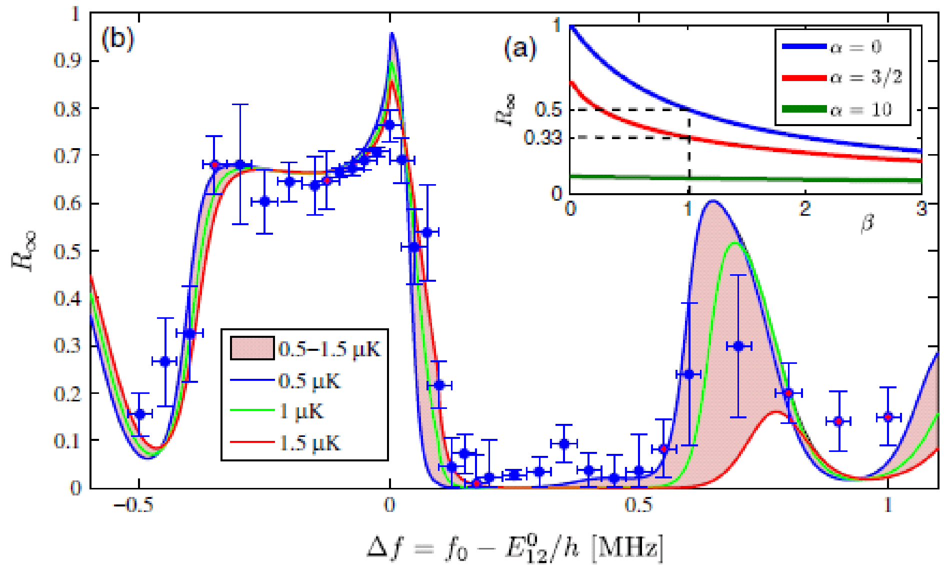
Using Time-Reversal Symmetry for Sensitive Incoherent Matter-Wave Sagnac Interferometry

Y. Japha, O. Arzouan, Y. Avishai, and R. Folman
Department of Physics, Ben-Gurion University, Be'er-Sheva 84105, Israel
(Received 6 December 2006; published 8 August 2007)

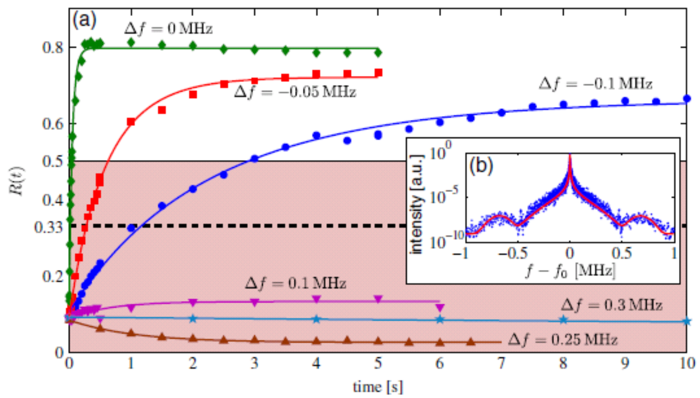
and now focusing on noise….

Noise can induce spin flips, heating, decoherence and asymmetries:

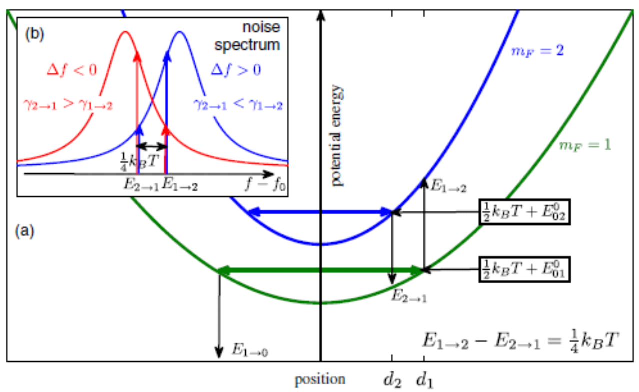
Colored noise (blue and red detuned) can induce random walks on the z axis of the qubit Bloch sphere.



S. Machluf et al. PRL 2010



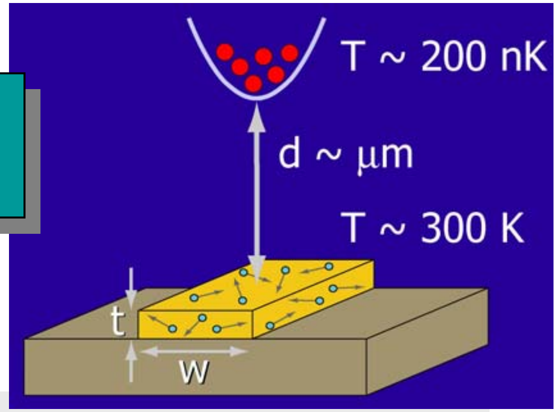
Gates usually have a qubit state dependent potential. Typically, due to the different position distribution, the transition from one state to the other is not Symmetric in energy.



So what can material engineering do to suppress noise?

3 examples concerning Johnson noise

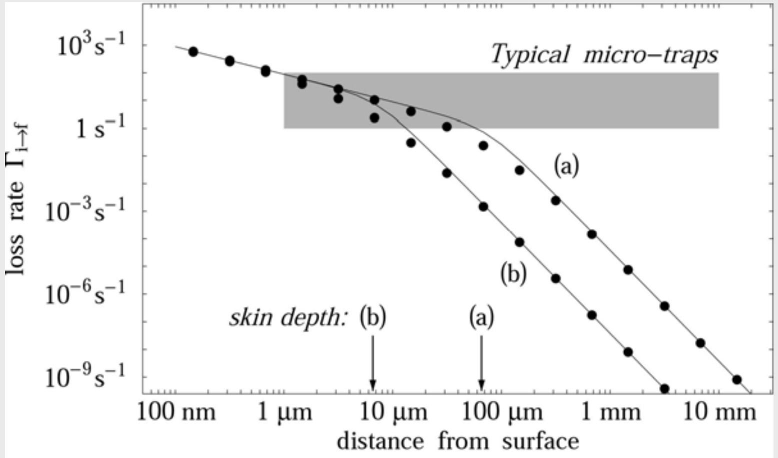
Theory of thermal noise – Carsten Henkel



Loss due to Johnson noise magnetic fields

$$\gamma \simeq 75\mathrm{s}^{-1}\frac{(\mu/\mu_{\mathrm{B}})^2(T_s/300\mathrm{K})}{(\varrho/\varrho_{\mathrm{Cu}})}(\mathrm{Tr}Y_{ij}\times 1\mu\mathrm{m})$$

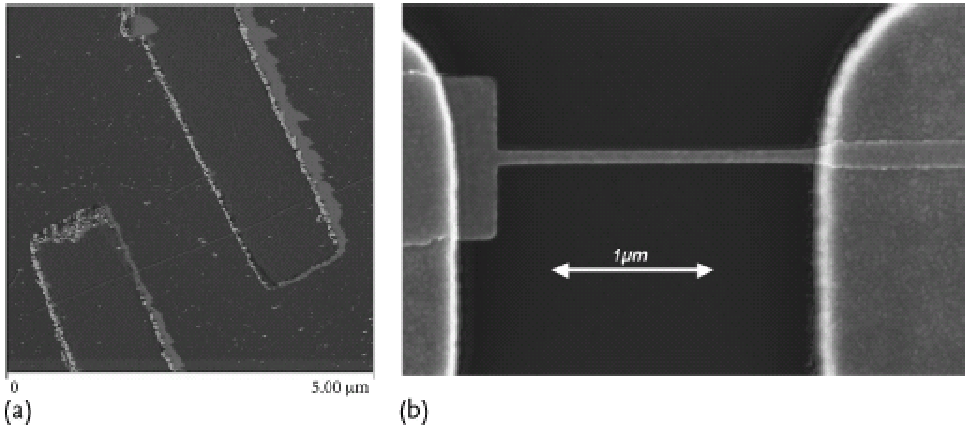
Geometry	Tr Y_{ij}
Half-space	π/h
Layer	$\pi d/h^2$
Wire	$\pi^2 a^2/(2h^3)$



Similarly for heating and decoherence!

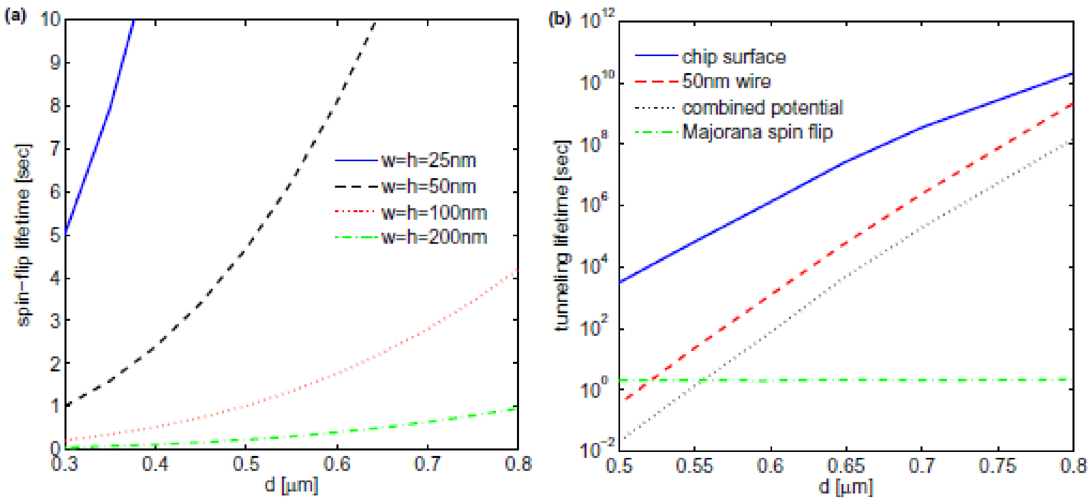
Carsten Henkel

1. In the case of thermally induced noise the trivial answer is to reduce metal:



P. Petrov et al. PRA 2010
R. Salem et al., NPJ 2010

Lifetime:



Current density goes up by two orders of magnitude from large wire to nano wire

But we can also play smarter tricks:

2. Do cooler metals produce less magnetic noise?

$$S_B^{ij}(\mathbf{x},\omega) = \frac{\mu_0^2 k_B T}{4\pi^2\rho} Y_{ij}(\mathbf{x})$$

The answer is NO, unless we contaminate the sample!

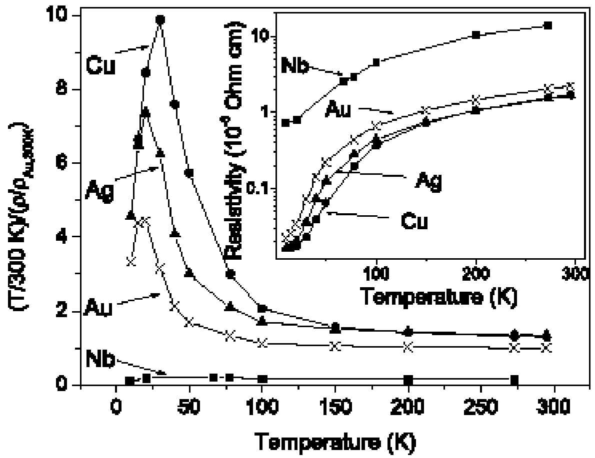


Fig. 1. Temperature dependence of the normalized magnetic noise calculated using equation (5) for wires made of copper (circles), silver (triangles) gold (crosses) and niobium (squares). The noise is normalized to the value for gold at $T = 300$ K. Inset: temperature dependence of the resistivity (extracted from [20]).

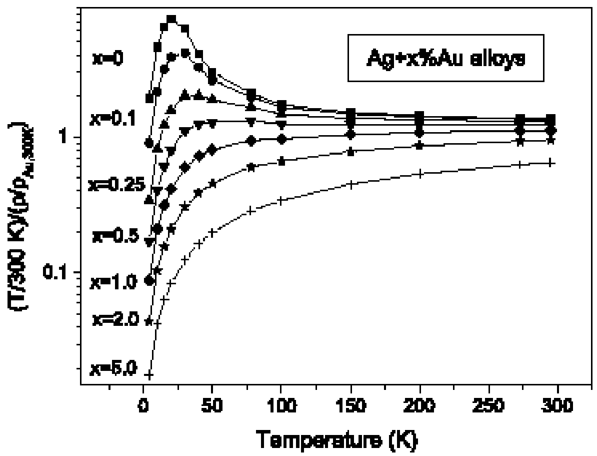
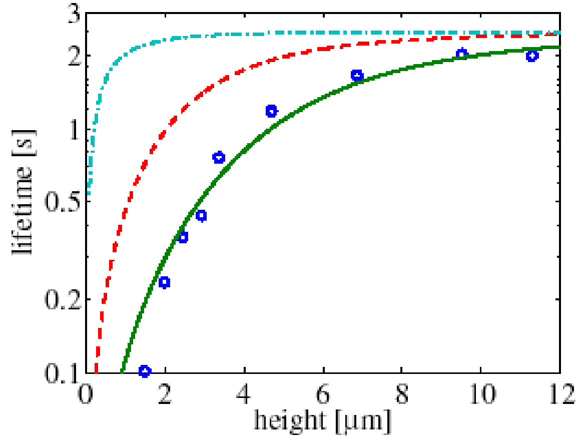


Fig. 4. Temperature dependence of the ratio T/ρ (normalized to its value for gold at 300 K) for silver and its alloys with gold: pure silver (squares), and with 0.1% gold (circles), 0.25% (triangles), 0.5% (inverted triangles), 1% (diamonds), 2% (stars), and 5% (crosses). The $\rho(T)$ dependence for alloys was calculated using the residual resistivity data given by [24,30]. Note the difference compared to Figure 1.



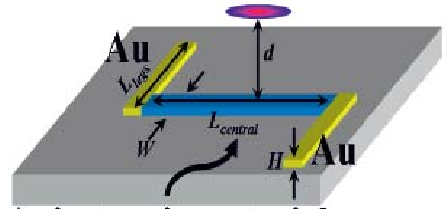
SC and Alloys: V. Dikovsky et al., EPJD (2005, 2009)

3. A final example:
orders of magnitude suppression of decoherence @ 300K

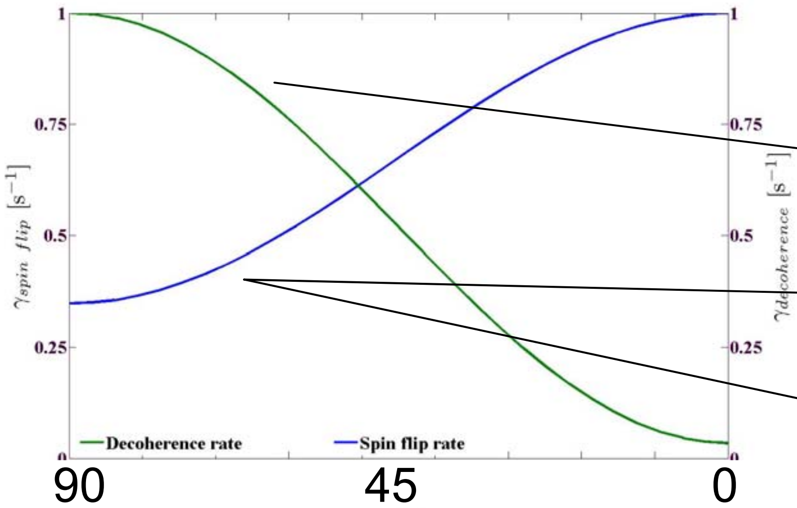
Can we suppress decoherence at room temperature?
NO!   Because it has exactly the same T/ρ dependence as in the spin flip rate.

$$\gamma_{\text{spin decoherence}} = \frac{\Delta\mu_{\parallel}^2}{2\hbar^2} S_{\parallel}(\vec{r};0) \qquad \Delta\mu_{\parallel} = \langle 2|\mu_{\parallel}|2\rangle - \langle 1|\mu_{\parallel}|1\rangle$$

Not true! The little parallel sign makes the difference!
Take anisotropic material:



Anisotropic material



Angle between magnetic moment and the good conductivity axis

follow the tensor

$$S_{xx}^{(\parallel)} \propto T\left(\sigma_{zz}X_{yy} + \sigma_{yy}X_{zz}\right)$$

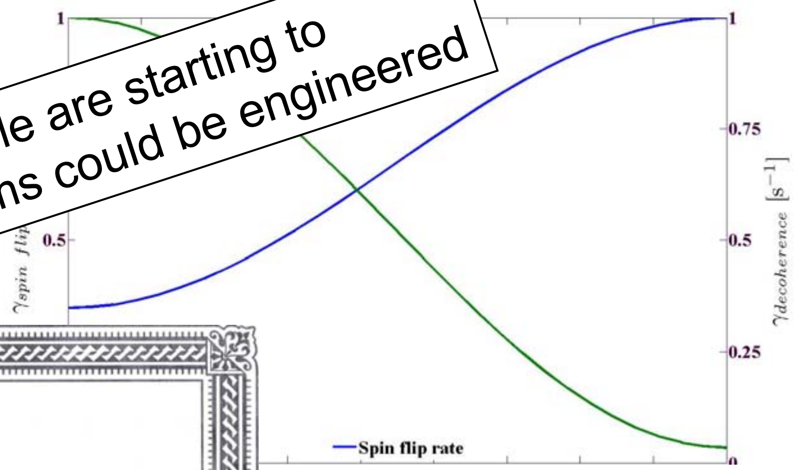
$$S_{yy}^{(\perp)} \propto T\left(\sigma_{zz}X_{xx} + \sigma_{xx}X_{zz}\right)$$

$$S_{zz}^{(\perp)} \propto T\left(\sigma_{yy}X_{xx} + \sigma_{xx}X_{yy}\right)$$

S – noise power spectrum T – temperature
σ – conductivity X – geometrical factor

Lifetime prediction may be readily verified if one can fabricate the surface:

It is nice to see that the material science people are starting to take notice of how environments of quantum systems could be engineered



45 0


MRS

The Materials Research Society hereby presents

TAL G. DAVID

with this certificate for the

GRADUATE STUDENT SILVER AWARD

for particularly significant and timely research presented by the recipient as an author or co-author at the 2008 MRS Fall Meeting

Cynthia A. Volkert, 2008 President, MRS

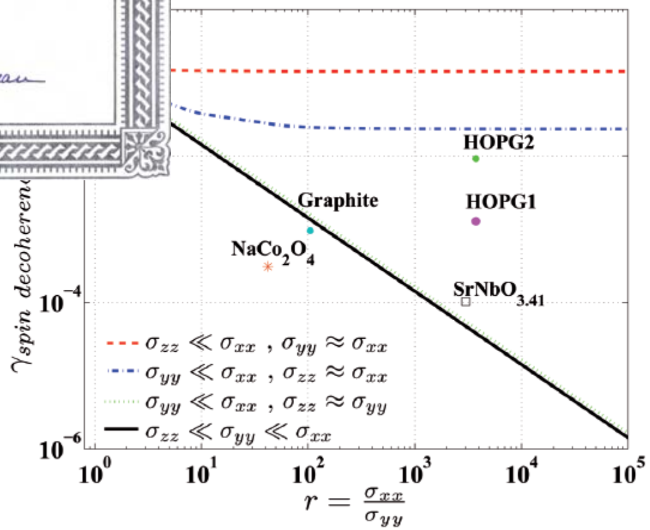
Julia R. Weertman, MRS Awards Chair

...ighly oriented pyro-gra...

ρ_{HOPG}/ρ_{Au} =18 ρ_{a}...

...tween magnetic moment ...good conductivity axis

But to meas... ...t be easy



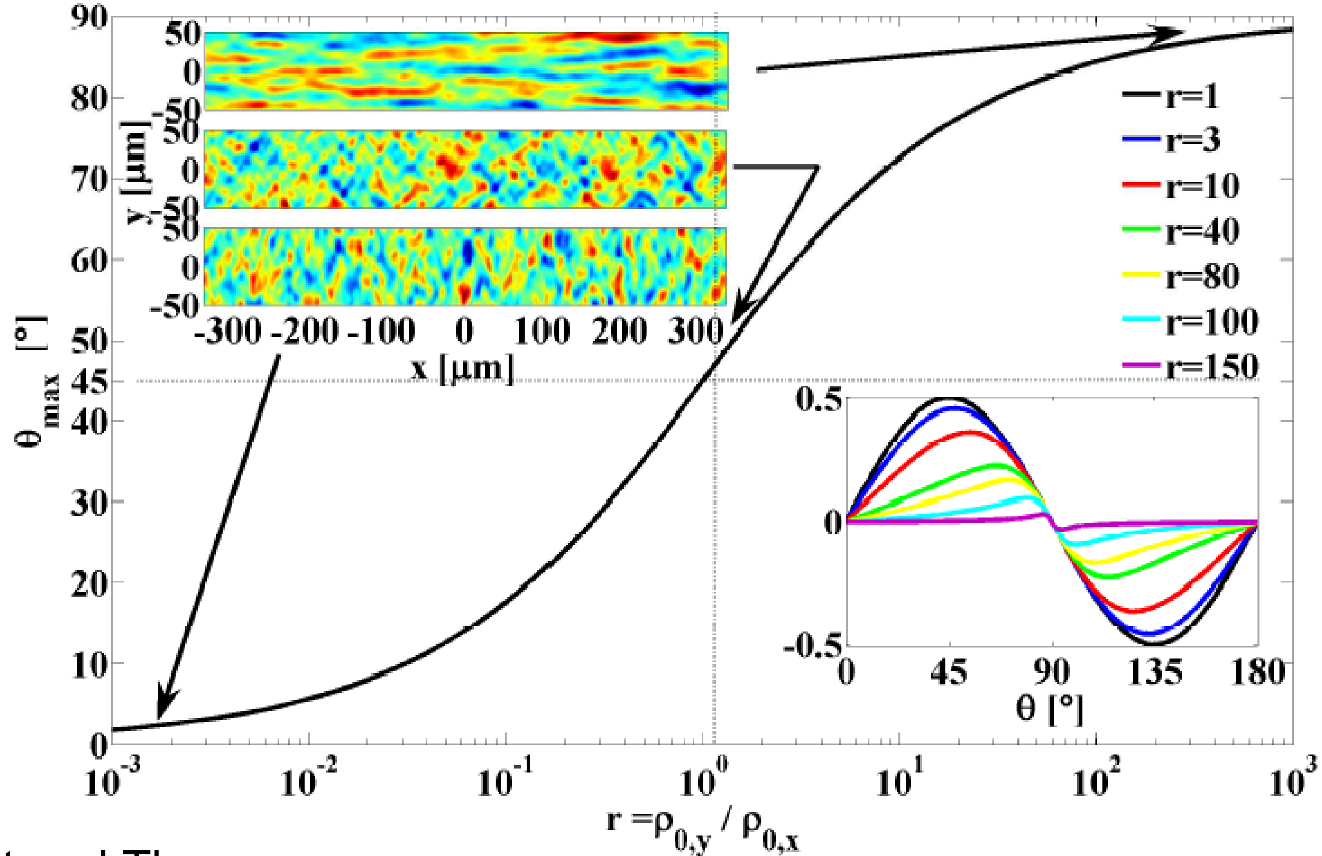
|1> = |2,1>   and |2> = |2,2> : first order Zeeman

But strong masking by broadening due to inhomogeneous trap (mag. field)

T. David et al., EPJD (2008) – highlight paper

PS - Anisotropic materials also affects electron scattering in previously unknown ways:

anisotropic materials change the angle
and the amplitude of static potential corrugations



Experiment and Theory
Y. Japha et al., PRB(R) (2008)
S. Aigner et al. Science (2008)

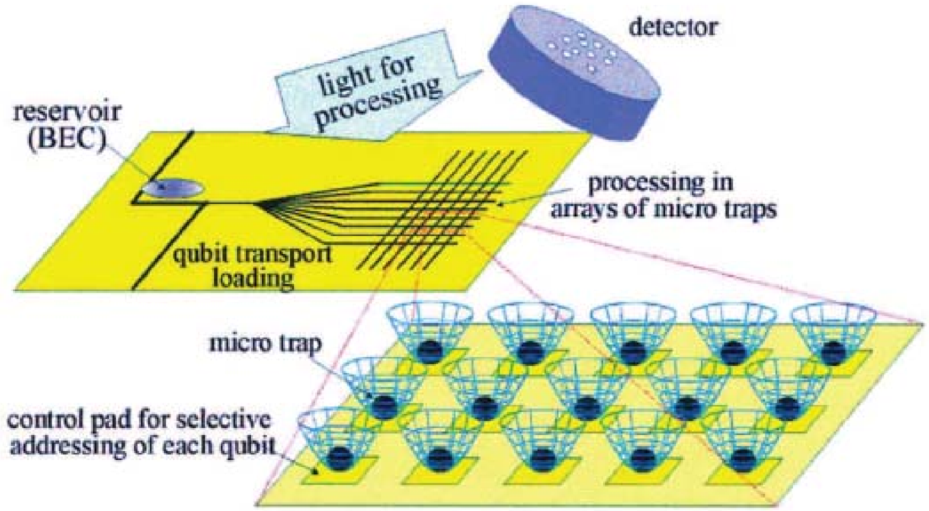
To conclude

• QIP is making impressive steps forward. However, the real thing is still quite a distance away

• It is hard to predict a time line or what the first realization will look like. Its not only a question of hardware but also of useful algorithms.

• Concerning hardware, hybrid systems look very promising. Concerning useful devices, quantum simulations will probably happen sooner.

• Whatever the eventual particle or eventual interactions, a useful QC device will probably require chip technology and considerable novel material science



• QIP is a great path for the study of the quantum-classical border

Food for thought (concerning timeline and importance):

►Our parents say that they grew up without the television

►We say that we grew up without the computer and mobile phone

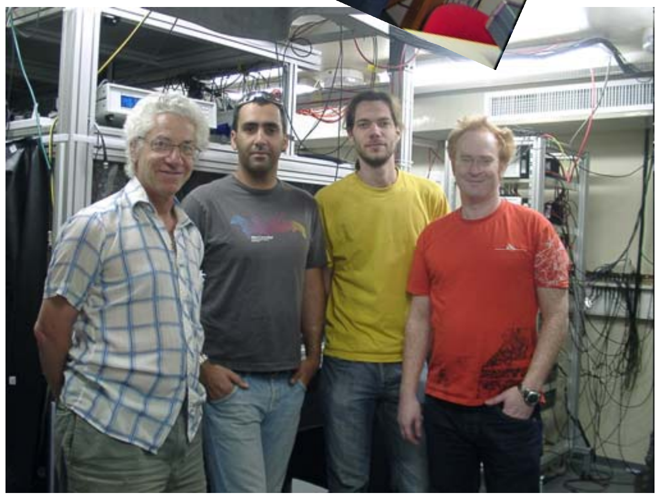
►Will our children say that they grew up without the quantum computer?

Thankyou to the lab team!

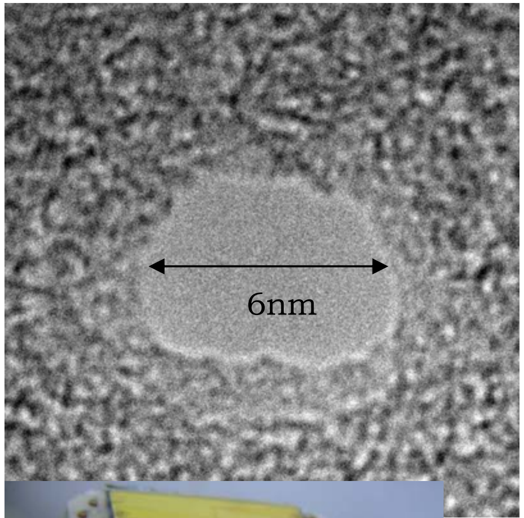
Shimon Machluf
Amir Waxman
Menachem Givon
Ruti Agou
Ramon Szmuk
Yair Margalit
Zina Binstock
Dr. Mark Keil
Dr. David Groswasser
Dr. Yonathan Japha
Dr. Daniel Rohrlich

Just left:

Jonathan Koslovsky
Dr. Tal David
Dr. Ran Salem
Dr. Julien Chabe
Dr. Plamen Petrov
Dr. Valery Dikovsky

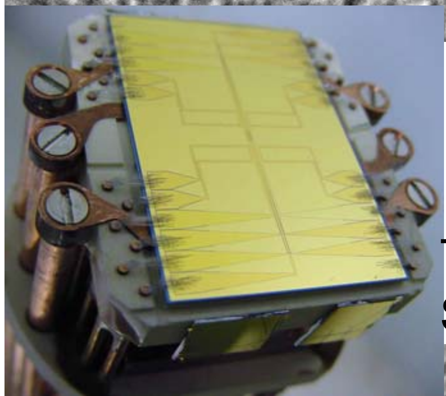


Red – contributed to the work on noise presented here

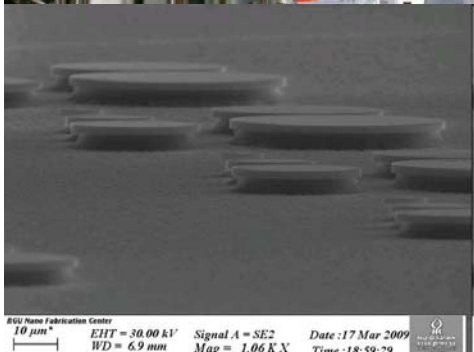


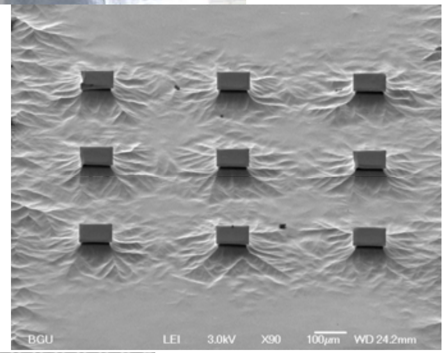
Our smallest structure to date (a 6nm hole through a SiN membrane)

Thankyou to the fab team!

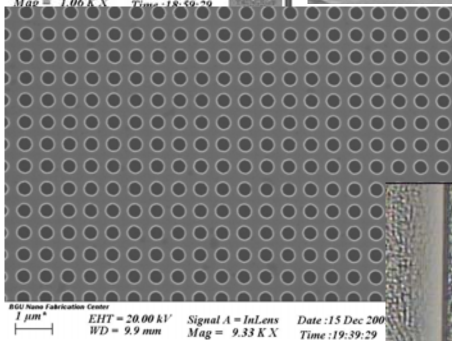


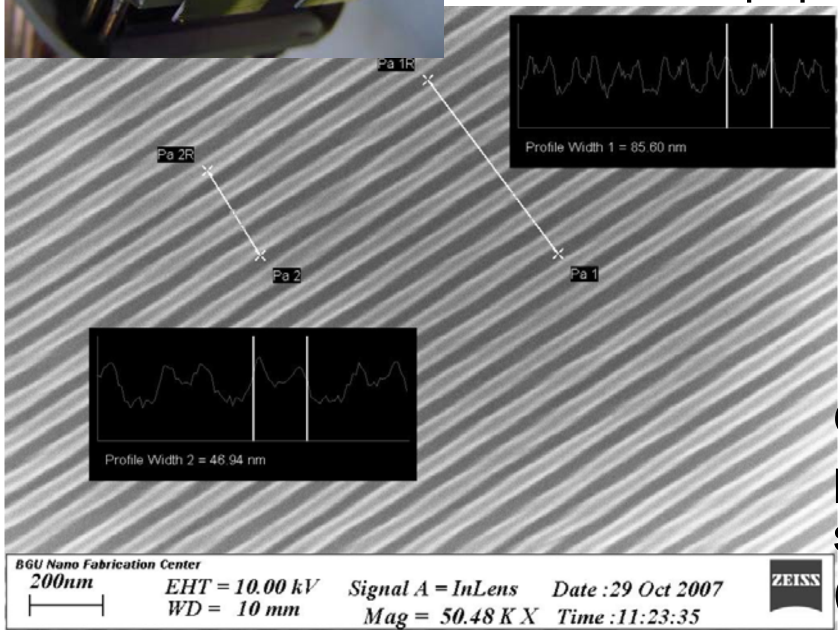
The chip used in our Science 2008 paper





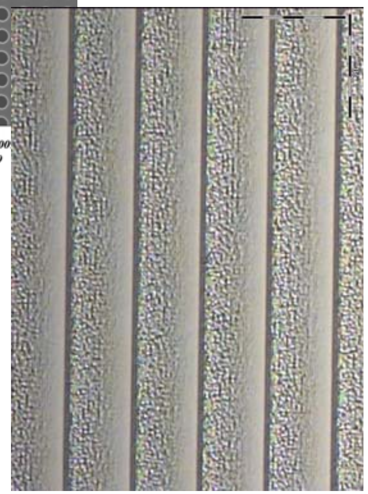
Hole arrays





Our smallest periodical structure to date (a 45nm wires)

Grey scale grating



And many thanks to you for listening….

Regarding quantum computers, Don't buy just yet!

However,
already now lots of interesting physics,
and you are invited to the QIP sessions!