Spin qubits
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Outline

Quantum information processing with spins

First QC: liquid state NMR

Solid state qubits

Spins in diamond

Application beyond QIP: sensing magnetic field
Push for Smaller

Nanoscale Technology

Ultra-short channel Si-MOSFET, IBM
0.5 \( \mu \text{m} \) wide, 0.1 \( \mu \text{m} \) channel

Single Electron Transistor (SET)
Quantum Bits

David DiVincenzo, 1996

1. A scalable physical system with well-characterized qubits.
2. The ability to initialize the state of the system.
3. Long relevant decoherence times, much longer than the gate operation time.
5. A qubit-specific measurement capability.
DiVincenzo’s Criteria


1. Well defined extensible qubit array
2. Preparable in the “000...” state
3. Long decoherence time
4. Universal set of gate operations
5. Single quantum measurements
Qubit Representations

- Electron: number, spin, energy level
- Nucleus: spin
- Photon: number, polarization, time, angular momentum, momentum (energy)
- Flux (current)
- Anything that can be quantized and follows Schrödinger's equation
Technologies Reviewed

• Liquid NMR
• Solid-state NMR, single spin in diamond, Si
• Quantum dots
• Superconducting Josephson junctions
• Ion trap
• Optical lattice
• All-optical
Timescales

• Can arrange these roughly according to strength of the qubit interactions with one another (and with the environment)
Liquid Solution NMR

Billions of molecules are used, each one a separate quantum computer.

Qubits are stored in nuclear spin of fluorine atoms and controlled by different frequencies of magnetic pulses.

First advanced experimental demonstrations to date, but poor scalability as molecule design gets difficult and SNR falls.

\[ \mathcal{H} = \sum_i \omega_i I^i_z + \sum_{i<k} \pi J_{ik} 2I^i_z I^k_z \]

Vandersypen, 2000
Dipolar interactions

Very narrow transitions: $T_2$ – a few seconds

The dipolar coupling depends on:
- the distance between the spins ($r$)
- the angle $\theta$ between the magnetic field $B$ and the vector connecting the spins

$$D \propto \frac{1}{r^3} \left(3 \cos^2 \theta - 1\right)$$

$$\langle 3 \cos^2 \theta - 1 \rangle \begin{cases} = 0 & \text{in isotropic liquids} \\ \neq 0 & \text{in solids or oriented media} \end{cases}$$
NMR Quantum Computation (1997 - )

Selected publications:

- Nature (1997), Gershenfeld et al., NMR scheme
- Nature (1998), Jones et al., Grover’s algorithm
- Science (1998), Knill et al., Decoherence
- Nature (1998), Nielsen et al., Teleportation
- Nature (2000), Knill et al., Algorithm benchmarking
- Nature (2001), Lieven et al., Shor’s algorithm

But mixed-state entanglement and hence computation is elusive.

Physics Today (Jan. 2000), first community-wide debates ...
NMR: state initialization

\[ \Delta E = h\nu = \hbar \gamma B \]

For \(^1\text{H}\) nuclei in 20 T field need temperature
T= 0.043 K

At room temperature magnetic field of 150 000 T is required
Pseudo-pure states

Mixed state

<table>
<thead>
<tr>
<th>polarization $p$</th>
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</thead>
<tbody>
<tr>
<td>$\uparrow\uparrow$</td>
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</table>

Effective pure state

Signal same as for pure state but amplitude $\sim 1/2^n$
Pseudo pure states

Thermalized state density matrix

\[ \rho_{\varepsilon_0} = \begin{pmatrix} \frac{1 + \varepsilon_0}{2} & 0 \\ 0 & \frac{1 - \varepsilon_0}{2} \end{pmatrix} \]

For ideal system

\[ \varepsilon_0 = \varepsilon_{\text{perfect}} = 1 \]
\[ \rho_{\varepsilon_{\text{perfect}}} = |0\rangle\langle 0| = \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} \]
Pseudo-pure states

Initial state of n-qubit system can be represented as a tensor product of states of the individual qubits

\[ \rho_{\text{init}}^{\{n\}} = \rho_{\varepsilon_0} \otimes \rho_{\varepsilon_0} \otimes \cdots \otimes \rho_{\varepsilon_0}. \]

“pseudo-pure state (PPS)” technique to perform computations with such highly mixed initial states

Initial mixed density matrix is transformed to a state

\[ \rho_{\text{PPS}}^{\{n\}} \equiv (1 - p) \mathcal{I} + p |\psi\rangle\langle\psi| \]

Mixture of the totally mixed state \[ \mathcal{I} = (1/2^n)I_{2n} \] and a pure state
Pseudo pure states

Unitary operations then leave the totally mixed state unchanged but do affect the pure state part, to perform the desired computation via entanglement of the pure state

For system of two qubits

\[
\rho_{\text{init}}^{n=2} = \begin{pmatrix}
\frac{1 + \epsilon}{2} & 0 \\
0 & \frac{1 - \epsilon}{2}
\end{pmatrix} \otimes \begin{pmatrix}
\frac{1 + \epsilon}{2} & 0 \\
0 & \frac{1 - \epsilon}{2}
\end{pmatrix}
\]

\[
\rho_{\text{init}}^{n=2} = \frac{(1 + \epsilon)^2}{4} \rho_{00} + \frac{1 - \epsilon^2}{4} \rho_{01} + \frac{1 - \epsilon^2}{4} \rho_{10} + \frac{(1 - \epsilon)^2}{4} \rho_{11}
\]
Pseudo-pure states

Unfortunately, in all existing PPS methods for n spins

\[ p = \frac{(1 + \varepsilon_0)^n - 1}{2^n - 1} < 2 \left( \frac{1 + \varepsilon_0}{2} \right)^n \]

signal is highly obscured by the completely mixed state, leading to an exponentially small signal-to-noise ratio, and hence, to the scaling problem.

**Shannon's Bound**: any loss-less compression scheme preserves the entropy \( H \) of the entire system
Can there be Speed-Up in NMR QC?

For Shor’s factoring algorithm, Linden and Popescu* showed that in the absence of entanglement, no speed-up is possible with pseudo-pure states.

Algorithmic Cooling

Basic idea (Boykin, Mor, Roychowdhury, Vatan, Vrijen)
– Pump out entropy of hot qubits by interaction with the environmental heat bath:
  • Use natural relaxation mechanisms to do this, i.e. "wait"
  • Hot qubits will naturally return to "room" spin temperature (i.e. natural bias $\varepsilon$)
  • This step referred to as "thermalisation" or "reset"

Algorithmic Cooling

cooling down 2 Carbons to a low temperature of 150 K

J. Baugh, O. Moussa, C. A. Ryan, A. Nayak and R. Laflamme
Nature 438, 470-473
All-Silicon Quantum Computer

10^5 ^{29}\text{Si} atomic chains in ^{28}\text{Si} matrix work like molecules in solution NMR QC.

Many techniques used for solution NMR QC are available.

A large field gradient separates Larmor frequencies of the nuclei within each chain.

No impurity dopants or electrical contacts are needed.

All-Silicon Quantum Computer

T2 time – 25s

Itoh, Solid State Communications 133 (2005) 747–752
$T_1$ and $T_2$ (and terminology)

$T_1$
- Longitudinal relaxation
- Spin-lattice relaxation
- Relaxation
- Energy relaxation

$T_2$
- Transverse relaxation
- Spin-spin relaxation
- Decoherence
- Phase randomization
- Dephasing

By definition: $T_2 < 2T_1$ In practice, often $T_2 \ll T_1$
Quantum 3-Bit Code: Bit Flip Error

- **Encoding** → $a |000> + b |111>$
- **Error channel**
  - Noise acts on each qubit independently
  - Probability noise, Markov process
Decoherence: noise from environment

• Qubit used to probe field fluctuations $X(t)$: $H_{\text{int}} = \sigma_{z,\text{qubit}} \cdot X(t)$

• Source of $X(t)$: ensemble of ‘coherent’ two-level systems (TLS)

• Each TLS is coupled (weakly) to thermal bath $H_{\text{bath,j}}$ at $T$ and/or other TLS

• GaAs – nuclear spins, characteristic timescale is given by dipolar interaction (100 µs)

Theory (partial list):
de Sousa, das Sarma, PRB 2003
Coish, Loss PRB 2004
Witzel, de Sousa, das Sarma, PRB 2005
Nuclear spins - the Kane proposal


Now good progress on some fabrication issues – Sydney, Melbourne
Challenge: spin readout
Nuclear spins - the Kane proposal

• Qubit is spin of $^{31}$P nucleus embedded in silicon crystal

• Evolution and measurement of qubits performed by controlling *individual* electron states nearby
Nuclear spins - the Kane proposal

• Coupling via weakly localized electron spins
Nuclear spins - the Kane proposal

• Readout performed by transferring qubits to electrons and measuring small changes in the shape of the electron distribution
current performance of various matter qubits

<table>
<thead>
<tr>
<th>Type of Matter Qubit</th>
<th>Coherence</th>
<th>Benchmarking</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(\omega_0/2\pi)</td>
<td>(T_2)</td>
</tr>
<tr>
<td>Trapped Optical Ion\textsuperscript{168,169} (^{40}\text{Ca}^+)</td>
<td>400 THz</td>
<td>1 ms</td>
</tr>
<tr>
<td>Trapped Microwave Ion\textsuperscript{170–172} (^9\text{Be}^+)</td>
<td>300 MHz</td>
<td>10 sec</td>
</tr>
<tr>
<td>Trapped Neutral Atoms\textsuperscript{173} (^{87}\text{Rb})</td>
<td>7 GHz</td>
<td>3 sec</td>
</tr>
<tr>
<td>Liquid Molecule Nuclear Spins\textsuperscript{174}</td>
<td>500 MHz</td>
<td>2 sec</td>
</tr>
<tr>
<td>e(^-) Spin in GaAs Quantum Dot\textsuperscript{66,86,89}</td>
<td>10 GHz</td>
<td>3 (\mu)s</td>
</tr>
<tr>
<td>e(^-) Spins Bound to (^{31}\text{P}:^{28}\text{Si}\textsuperscript{92,93}</td>
<td>10 GHz</td>
<td>60 ms</td>
</tr>
<tr>
<td>Nuclear Spins in Si\textsuperscript{94}</td>
<td>60 MHz</td>
<td>25 sec</td>
</tr>
<tr>
<td>(\textit{NV}^–) Center in Diamond\textsuperscript{105,110,113}</td>
<td>3 GHz</td>
<td>2 ms</td>
</tr>
<tr>
<td>Superconducting Phase Qubit\textsuperscript{128,136,175}</td>
<td>10 GHz</td>
<td>350 ns</td>
</tr>
<tr>
<td>Superconducting Charge Qubit\textsuperscript{134,176,177}</td>
<td>10 GHz</td>
<td>2 (\mu)s</td>
</tr>
<tr>
<td>Superconducting Flux Qubit\textsuperscript{129,178}</td>
<td>10 GHz</td>
<td>4 (\mu)s</td>
</tr>
</tbody>
</table>

T. Ladd et al., „Quantum computers“ Nature, 2010
Spin qubits in Diamond
Fedor Jelezko, University of Stuttgart

magnetometry

quantum cryptography


quantum computing

Quantum Communication Victoria
http://qcvictoria.com/
Beveratos et al., *PRL* 89, 187901 (2002)
Wu et al. Optics Express, 14, 1296 (2006)

Neumann et al., *Science* 320, 1326 (2008)

Gurudev Dutt et al., *Science* 316, 1312 (2007)
Qubits

Superconducting circuits

Quantum dots

Early ideas:
P.R. Hemmer, S. Kilin, T. Kennedy, D. Awschalom, FJ, J.Wrachtrup ...

Ion traps

Atoms

Photons

temperature

300K

mK
Diamond: synthetic vs natural

Concentration of impurities: below $10^{12}$ cm$^{-3}$

D. Twitchen, Element 6 Ltd
B. Linares, Apollo diamonds inc
J. Buttler, Naval research
J. Achard, Université Paris 13
Y. Isoya, Tsukuba
M. Nesladek, Hasselt
Single N-V centers implantation

Set-up
Single center signature: photon antibunching

\[ g^{(2)}(\tau) = \frac{\langle I(t)I(t+\tau) \rangle}{\langle I(t) \rangle^2} \]

Photon stream

Single photon source:

First commercial implementation
QCV, Melbourne, 2008

Transform-limited single photons @4K
Batalov et al., PRL 2008
Diamond color centers: source of single photons for test of QM

Experimental realization of Wheeler's delayed-choice gedanken experiment
Jacques V, Wu E, et al.
SCIENCE 315 966-968 (2007)
Room temperature spin readout

- Meta-stable singlet
  - ~30% suppressed fluorescence for Sx and Sy states
- Sz cycling transition gives ~ 1000 photons before spin flip

Experiments
Theory
Recent work: N. Manson (ANU)
Coherent control (e-spin)

- coherently driven electron spin oscillations

Data: DARK06071201_C
Model: rabidec
Equation: \( y = y_0 + A \cos\left(\frac{x - x_0}{\text{period}} \times 2\pi\right) \times \exp\left(-\frac{x}{\text{decay}}\right) \)

- No weighting
- \( \chi^2/\text{DoF} = 0.00009 \)
- \( R^2 = 0.98903 \)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>( y_0 )</td>
<td>0.97051</td>
<td>0.00149</td>
</tr>
<tr>
<td>( A )</td>
<td>0.1285</td>
<td>0.00438</td>
</tr>
<tr>
<td>( x_0 )</td>
<td>-0.00204</td>
<td>0.00028</td>
</tr>
<tr>
<td>( \text{period} )</td>
<td>0.05536</td>
<td>0.00027</td>
</tr>
<tr>
<td>( \text{decay} )</td>
<td>3.9136</td>
<td>9.6014</td>
</tr>
</tbody>
</table>

fluorescence intensity [a.u.]

microwave pulselength \( \tau \) [\( \mu \)s]

Jelezko et al. PRL 2004
Phase memory of diamond spin qubit: Ramsey fringes

\[ \varphi = \frac{1}{\sqrt{2}} (|\uparrow\rangle + |\downarrow\rangle) \]

\[ \rho_\varphi = \frac{1}{2} \begin{pmatrix} 1 & 1 \\ 1 & 1 \end{pmatrix}, \]

\[ I_{fl} (\text{a.u.}) \]

Free precession time (µs)
Decoherence via coupling to nuclear spins

\[
\omega_z(t) = \gamma_S B + \frac{1}{2} \sum_n A_n \sigma'_n(t)
\]

\[
\sigma_{nm} = \pm 1
\]

\[
\omega_z(t) = \sum_{n \neq m} \Delta_{nm} \sigma_{nm}(t) + \text{const}
\]

\[
\Delta_{nm} = \left| A_n - A_m \right| / 2
\]

Recent work: decoherence due to coupling to electron spin bath:
Quenching Spin Decoherence

\[ \frac{1}{T_2} \equiv CP_{m_s=-1/2}P_{m_s=1/2} + \Gamma_{\text{res}} \]

\[ = \frac{C}{(1 + e^{T_{Ze}/T})(1 + e^{-T_{Ze}/T})} + \Gamma_{\text{res}}, \]

Takahashi
Coherence time, nuclear spin bath

Balasubramanian et al., Nature Materials 2009
Ultralong coherence of single electron spin

Balasubramanian et al. Nature Materials 2009

99.99 % $^{12}$C diamond, Daniel Twitchen, E6

Echo: $T_2 > 4$ ms
Decoherence, frozen core

$C_{13}$ diffusion constant: \[ D \propto \frac{r^2}{T_2} \]

Roughly $10^2 ^{13}\text{C}$ are in the frozen core
The Signature of $^{13}\text{C}$ in the 1$^\text{st}$ Shell

- EPR Spectrum of NV’s $m_s=0 \rightarrow -1$ transition

![EPR Spectrum Diagram]

- Microwave Frequency [MHz]
- Fluorescence Intensity [a.u.]
Two nearest-neighbor $^{13}$C nuclear spins coupled to a single NV center
Coherent manipulation of the register

1. Initialization laserpulse
   - Ground state spin sublevels
     - $|00\rangle$
     - $|01\rangle$
     - $|10\rangle$
     - $|11\rangle$
     - $m_s = 0$
     - $m_s = -1$

2. MW $\pi$-pulse
   - Stepwise increasing RF-pulselength $\tau$

3. MW $\pi$-pulse
   - Readout laserpulse
   - Readout & re-initialization

Fluorescence Intensity [a.u.]
Radio Frequency Pulse Length [ms]

Rabi nutation on RF1

$\frac{1}{\sqrt{2}} (|00\rangle \pm |10\rangle)$
Ramsey fringes on single $^{13}$C nuclear spin

Echo measurements: $T_2 > 40$ ms @ 300K

Gurudev Dutt et al. SCIENCE 1312 (2007)
Entangling nuclear spins

\[ \Phi^- = \frac{1}{\sqrt{2}} \begin{pmatrix} 00 \rangle + |01\rangle \end{pmatrix} \]

- coherent control of four RF transitions
- Quantum state tomography: \( \rightarrow \) fidelities up to 0.97
- lifetimes more than 3 ms

\[ \Psi^- = \frac{1}{\sqrt{2}} (|10\rangle + |01\rangle) \]

P. Neumann et al., *Science* 320, 1326 (2008)
Entangling electron and nuclear spins

\[ \text{GHZ} = \frac{1}{\sqrt{2}} (|111\rangle + |000\rangle) \]

\[ \text{W} = \frac{1}{\sqrt{3}} (|110\rangle + |011\rangle + |101\rangle) \]

- fidelities \( \geq 0.85 \)
- lifetimes:
  - 1 \( \mu \)s (e\(^-\)-character)
  - 3 ms (n-character)

\( \tau = 0 \)

\( \tau = 2.4 \mu s \)

\( \tau = 4.4 \mu s \)

P. Neumann et al., *Science* 320, 1326 (2008)
1. Alice and Bob each possess one qubit of an entangled qubit pair.
2. Alice performers one of four possible local operations to her qubit.
3. Then she sends her qubit to Bob.
4. Bob can perform a Bell state measurement in the Bell basis.

The 4 possible outcomes correspond to 2 bits of classical information.

→ Transmission of 2 bits of classical information by transmission of one (a priori entangled) qubit.

Initial state:
\[
\Phi^- = \frac{1}{\sqrt{2}} (|00\rangle - |11\rangle)
\]

Operations:
\[
\Phi^+ = \frac{1}{\sqrt{2}} (|00\rangle + |11\rangle)
\]
\[
\Psi^- = \frac{1}{\sqrt{2}} (|01\rangle - |10\rangle)
\]
\[
\Psi^+ = \frac{1}{\sqrt{2}} (|01\rangle + |10\rangle)
\]

Experimental realization of SDC

\[ I = \Phi^- = \text{do nothing} \]
\[ U_1 = \Phi^+ = 2\pi (\text{MW}) \]
\[ U_2 = \Psi^- = \pi (\text{RF2}) + \pi (\text{RF3}) \]
\[ U_3 = \Psi^+ = 2\pi (\text{MW}) + (\pi (\text{RF2}) + \pi (\text{RF3})) \]
Results

Population after projection sequence depends on the operation that Alice has chosen.

→ Bob can distinguish between four possibilities after having received one qubit from Alice.
Small scale (4-5 qubits) quantum register

- Testing possibility to create larger scale (4-5 qubits) quantum register
  Dipolar magnetic coupling between defects

\[ B^{dip} = \left( \frac{\mu_0}{4\pi} \mu \right) \sqrt{3 \cos^2 \theta - 1} / r^3 \]

For a distance of about = 50 nm is interaction is roughly 0.45 kHz - within \( T_2 \) time

How to address optically closely spaced qubits?
Deterministic single ion implantation out of a Paul trap

cooperation with F. Schmidt-Kaler (Ulm)

J. Meijer et al., cond-mat/0508756

Sympathetic Cooling of N$^+$ Ions
H. C. Nägerl, Innsbruck, unpublished
Nonlinear Optical Microscopy

Excitation beam saturates 2-level system

Related technique: STED, S. Hell (Göttingen)
NV defects – Han et al., Nano Letters (2009)

Excitation beam profile

Saturated fluorescence profile of a point-like emitter

Dark spot shows the fluorescent center position.
Subwavelength optical addressing of single spins
Coherent coupling of two single spins

\[ H_{\text{dip}} = \frac{\mu_0 g^2 \mu_B^2}{4\pi r^3} \left[ \hat{S}_{NV1} \cdot \hat{S}_{NV2} - 3(\hat{S}_{NV1} \cdot \vec{r})(\hat{S}_{NV2} \cdot \vec{r}) \right] \]

Scalable quantum processor in diamond
Neumann et al., Nature Physics, 2010
Sensing one NV using the other superposition acts as magnetometer

$$S_{\text{NV B}} = 0 - 1 + 1$$

Signal NV A

$T_{2}^* = 15\mu$s

$H_{DD} \approx 40\pm8$ kHz

state of NV B +1 0 -1

$mw$
Coherent coupling of two single spins

\[ H_{\text{dip}} = \frac{\mu_0 g^2 \mu_B^2}{4\pi r^3} \left[ \hat{S}_{NV1} \cdot \hat{S}_{NV2} - 3 \left( \hat{S}_{NV1} \cdot \hat{r} \right) \left( \hat{S}_{NV2} \cdot \hat{r} \right) \right] \]

\[ \Delta \varphi = \gamma \cdot \delta B \cdot T \]

Conditional spin flip - Quantum logic operations
Relative position of the two NVs

\[ d = 9.8 \pm 0.4 \text{nm} \]

Error Volume < 1 unit cell
Quantum information with atoms and photons

Qubit representations

Spin states of atoms

- Long coherence times
- Easy single-qubit gates
- Easy to store
- Difficult to “transmit”

Photon number or polarization

- Easy single-qubit gates
- Easy to transmit
- Difficult to store
Hybrid approaches

• Pioneering example: quantum optical interface
  Non-local coupling of quantum bits by absorbing
  or emitting a photon in a controlled way

  ![Quantum Optical Interface Diagram]


• Broad effort in AMO community:
  single neutral atoms, ions, atomic ensembles, solid-state emitters

• New approaches to q.networks: probabilistic, cluster state techniques etc

• Remarkable new interconnects:
  optical, microwave, mechanical domains
Small scale quantum processor

quantum repeater
(few qubit quantum processor)

Amplifier
Diamond quantum repeater
following early ideas, Cirac, Zoller

• Chain of quantum repeaters with $\geq 2$ qubits/node
  – idea: MD Lukin et. al. PRL 96 070504 (2006):

  - e electron spin: coupling to light field, entanglement creation
  - n nuclear spins: entanglement storage and purification

  Basic requirements for purification: Coherent control and entanglement of nuclear spins
**Scheme of probabilistic entanglement generation via interference**

**Alice**

Photon-mediated entanglement

**Bob**

**Atom B**

Classical Pump (weak)

Preparation

|1⟩_A |1⟩_B  ↔  Excitation (weak)

|1⟩_A |1⟩_B + |3⟩_A |1⟩_B + |1⟩_A |3⟩_B  ↔  Click on detector measuring 3-2 transition

Experiments trapped ions: Olmschenk et al. Science 2009: 486
Mapping of spin state into photons

In collaboration with Ch. Santori (HP) and P.R. Hemmer (Texas A&M)
quant-ph/0607147

\[ |3\rangle \]

\[ |1\rangle \]

\[ |2\rangle \]

\[ \text{coupling} \]

\[ \text{pump} \]

\[ \Lambda \text{-type level scheme, with 2 allowed transitions} \]

\[ |\text{dark}\rangle = \cos \theta |1\rangle - \sin \theta |2\rangle \]

\[ \tan \theta = \frac{\Omega_p}{\Omega_c} \]

\[ \Omega = -\tilde{d}\tilde{E}_0/\hbar \]

Santori et al.
Inhomogeneous broadening

Fluorescence, photocounts

Laser Detuning, GHz
Electric tuning of excited state wavefunction

Tamarat et al., PRL 2007
Photonics crystals in architecture

Gaudi
Diamond nanophotonics

Photonic crystals can localize light into extremely small volumes $V \sim (\lambda/n)^3$ with quality factors $Q \sim 10^6$; large $Q/V$

- Lattice Constant: $a=210\,nm$
- Hole radii: $r=58\,nm$, $r_A=60\,nm$
- Hole Shifts: $D_A=12\,nm$, $D_B=7\,nm$, $D_C=4\,nm$.

$Q \approx 1.3 \times 10^6$, and $V_m \approx 1.78 \times (\lambda/n)^3$
Quantum interfaces based on PCs: recent advances

Strong coupling, single photon nonlinear optics with semiconductor QDs with GaAs photonic crystal cavities

J.Vuckovic (Stanford), A.Imamoglu (ETH), J.Finley (Munich)

Challenge: extend these techniques to other qubits with better coherence properties, other materials, hybrid qubit/cavity systems, e.g. diamond+GaP cavities
Diamond cavity (first results, I. Bain, J. Salzmann, Technion)
Coupling of optical transition to plasmonic resonance

Sub-wavelength localization and guiding electromagnetic field on conducting wires results in strong coupling of single atoms to plasmon field

Example: proximal atom emission guided almost completely into the wire accompanied by large enhancement

Single dipole emission into wire

Related work
Theory, Hemmer et al quant-ph/060322
Single photon plasmonics

Kolesov et al., in press

Wave–particle duality of single surface plasmon polaritons

Kolesov et al. Nature Physics 2009

Wire ends

Single plasmon antibunching

Normalized coincidence counts

Time delay (ns)

Lifetime 5 ns
Wave–particle duality of single surface plasmon polaritons

Self-interference of single surface plasmon polaritons.
Manipulating single atoms: from gedankenexperiment to reality

Solvay, fifth conference participants, 1927
Quantum non-demolition (QND) readout of spin qubits

Spin can be measured and after the measurement the spin is still in measured state (ideal projective measurement)

\[ |+1/2\rangle + |-1/2\rangle \]

\[ S_z \uparrow \]

\[ |+1/2\rangle \]

\[ S_z \uparrow \]

\[ |+1/2\rangle \]

• Is important for **measurement-based quantum computation** schemes (one-way-quantum computer) and **quantum error correction**
• is required for adaptive measurements schemes, which allow to **measure better than the standard quantum limit**
• can be used for **qubit initialisation** (by measurement)
History of QND

How to evade the confrontation with the uncertainty relations

Landau, Peierls 1931

Erweiterung des Unbestimmtheitsprinzips für die relativistische Quantentheorie.

Von L. Landau und R. Peierls in Zürich.

(Eingegangen am 3. März 1931.)

“...if there existed an interaction Hamiltonian depending on velocity only, one would be able to measure the velocity of a free particle with the arbitrary high precision.”

Further, an incorrect conclusion was given:
” ...such a Hamiltonian does not exist, and therefore such a measurement is not possible”

However, important point was discussed: interaction Hamiltonian is crucial for back-action
Using single atom as measurement device

Science, 309, 749 (2005)

Spectroscopy Using Quantum Logic

P. O. Schmidt,*† T. Rosenband, C. Langer, W. M. Itano, J. C. Bergquist, D. J. Wineland

We present a general technique for precision spectroscopy of atoms that lack suitable transitions for efficient laser cooling, internal state preparation, and detection. In our implementation with trapped atomic ions, an auxiliary "logic" ion provides sympathetic laser cooling, state initialization, and detection for a simultaneously trapped "spectroscopy" ion. Detection is achieved by applying a mapping operation to each ion, which results in a coherent transfer of the spectroscopy ion's internal state onto the logic ion, where it is then measured with high efficiency. Experimental realization, by using $^9\text{Be}^+$ as the logic ion and $^{27}\text{Al}^+$ as the spectroscopy ion, indicates the feasibility of applying this technique to make accurate optical clocks based on single ions.

Repellative Readout of a Single Electronic Spin via Quantum Logic with Nuclear Spin Ancillae

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N

Vacancy

C

C

C

n-spin state $|\Psi\rangle$

e-spin
correlate n- and e-spin

measure e-spin
QND nuclear spin readout using CNOT gate

\[ |-1_n\rangle |0_e\rangle \rightarrow |-1_n\rangle |-1_e\rangle \]

\[ |0_n\rangle |0_e\rangle \rightarrow |0_n\rangle |0_e\rangle \]

Ph. Neumann et al., unpublished

Proposal to use quantum logic for QND:
T. C. Ralph, S. D. Bartlett, J. L. O'Brien,
Quantum jumps of single nuclear spin

Repetitive QND measurements reveal quantum jumps of a single nuclear spin (in diamond at room temperature)
Diamond Quantum Technologies

Room temperature solid state quantum register
Test bed for solid state quantum physics

Key ingredients are demonstrated:

• single atom doping
• Coherent control and single spin readout
• First three qubits in solid state

Next steps

Achieving high positioning accuracy for qubits
Spin-photon entanglement

Novel surprising applications: single spin magnetometry
The Quantum Zeno-effect

• To perform a coherent evolution is a Sisyphean task if someone else is measuring all the time.
The Quantum Zeno-effect

- Coherent evolution frozen by projective measurement without disturbance
  - \( \pi \)-pulses flip spin
  - also segmented pulses

\[ \Rightarrow \text{projection on } z \text{-axis} \]

- Destruction of coherence upon measurement
  - \( \rightarrow \) projection on \( z \)-axis
Quantum Zeno-effect

\[ \frac{1}{2} \left( 1 - \cos^N \left( \frac{\pi}{N} \right) \right) \]
Quantum applications: Metrology & sensing

Quantum coherence, logic, entanglement for metrology
Better clocks: one of the early motivation to study entanglement in AMO systems

New avenues:
use solid-state systems extend to new domains, e.g. nanometer-scale sensing
Sensing magnetic fields

\[ H = \hbar D S_z^2 + g \mu_B B_z S_z \]

- Zeeman effect on single spin
- Atomic vector magnetometer.
- Far field probe.
- Absolute - No calibration.
- Sensitivity depends on the line width.
  - Improved using coherent manipulations

NV parameters:

\[ T_2^* \sim 1 \mu s; T_2 \sim 1 ms \]

\[ \eta_{T_2} \sim 18 nT/\sqrt{\text{Hz}} \] as opposed to \[ \eta_{T_2^*} = 0.5 \mu T/\sqrt{\text{Hz}} \]
Diamond atomic magnetometer

A new sensor that makes use of single NV spin close to diamond surface to detect magnetic fields via Zeeman effect

\[ B = \frac{\mu_0 \hbar \gamma_e}{r^3} \left[ 1 - 3 \cos^2(\theta) \right] S_z \]

<table>
<thead>
<tr>
<th>Spin</th>
<th>Distance (r)</th>
<th>Field</th>
<th>Required T_2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron</td>
<td>10 nm</td>
<td>1µT</td>
<td>~ 2 µs</td>
</tr>
<tr>
<td>Proton</td>
<td>10 nm</td>
<td>1nT</td>
<td>~ 2 ms</td>
</tr>
</tbody>
</table>

NV nanomagnetometry


- Scanning nano-magnetometer: Nanodiamond on the tip of an atomic force microscope
- Spatial resolution: 4 nm, magnetic field sensitivity: 100 nT/\sqrt{\text{Hz}}
Solid state magnetic field sensors


Balasubramanian et al., Nature (2008)

Balasubramanian et al., Nature Materials (2009)
Application to nanoscale sensing and imaging in biology

potential applications in micro MRI, biophysics, neuroscience
Collaboration P. R. Hemmer (Texas A&M), P. Curmi (INSERM)

Current efforts:
Sensing bioprocesses at nanoscale

Balasubramanian et al, unpublished
Diamond Quantum Technologies

Room temperature solid state quantum register
Test bed for solid state quantum physics

Key ingredients
• single atom doping
• Coherent control of small spin registers (up to three qubits)
• QND readout

Current effort
Spin-photon entanglement (recent work, Harvard)

Coupling to MW cavities
D. Esteve (Saclay), J. Schmiedmayer (Vienna), J. Twamley (Sydney)

Technically simple single spin detection:
Quantum optics in undergraduate lab!