Hybrid approaches to quantum information science
Challenge of simultaneous isolation and control of many-body system
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But: do not interact, hard to store
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- Charged solid-state systems: stability, integration, strong interactions
  
  But: live in complex solid-state environment, hard to control
Hybrid approaches to quantum information

aim: address key challenges in QIS

• Hybrid tools to explore new qubits
• Hybrid architectures: combining useful features of different systems
• Outlook: new applications of hybrid systems
• Outlook: integrating hybrid experimental technologies
Hybrid tools for exploring new qubits
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one example
Example: control of single electron & nuclear spins using Nitrogen-Vacancy impurities in diamond
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- Quantum control techniques from quantum optics, ESR & NMR
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  • Understanding physics of mesoscopic (spin) environment
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✓ Enabled by:

• Single molecule optical spectroscopy
• Quantum control techniques from quantum optics, ESR & NMR
• Understanding physics of mesoscopic (spin) environment
• Advances in material science
Control of single electron spin

Use light to isolated, polarize, readout electron spin state at room T
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Friday, April 24, 2009
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- Pioneering work
  F.Jelezko, J.Wrachtrup (Stuttgart)
  D.Awschlom (UCSB)

- Near single shot readout at low T
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- Electron precession decay time (average over many runs): \( T_2^* \approx 1 \mu s \)
- Electron decoherence time (spin echo): \( T_2 \approx 1 \text{ ms} \)

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Ion implantation: isotopic engineering of single spins

Spatially resolved photoluminescence map

1 mm

Anti-bunching indicates single spin

Hyperfine splitting $^{15}$NV

Single spin resonance

(G.F. Fuchs et al., 2009)
Picture of single electron environment

- Obtained through detailed spectroscopy of individual NV centers
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$^{13}$C nuclei decoherence
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13C nuclei
decoherence
Proximal nuclei are different:
strong hyperfine, can be isolated

R. Hanson et al, Science (2008)
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• Current efforts:
  reducing 13C concentration
  controlling & using proximal nuclear spins:
  realization of few qubit registers

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Improving coherence via materials engineering

✓ New development: ultra-pure CVD grown diamond enriched $^{12}$C isotope
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✓ First results: ultra-long coherence in Ramsey measurements

$T_2^*> 100$ microseconds, exceptional coherence!

Controlling nuclear spins in electron environment: recent work
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✓ Magnetic detection, control of individual $^{13}$C nuclei in electron environment

• Polarization (sub μK cooling), control, readout of single nuclei
• Long lived (~1s) quantum memory in single nuclei at room T
• Controlled few-spin systems, entanglement of 3 spins

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Application: repetitive readout of electronic spin using proximal nuclear spins

✓ Idea: map electronic spin to nearby nuclear spin(s), repetitively measure nuclear spin
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$|\Psi\rangle \rightarrow |0\rangle \rightarrow |0\rangle \rightarrow |0\rangle \rightarrow \ldots$
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![Diagram showing the mapping of electronic spin (e-spin) to nearby nuclear spin (n-spin)]
Application: repetitive readout of electronic spin using proximal nuclear spins

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\[ e \]

\[ n \]

\[ |\Psi\rangle \]

\[ |0\rangle \]

\[ 1 \]

\[ 2 \]

\[ \ldots \]
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![Diagram of electronic and nuclear spins]
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\[ n\text{-spin} \]

\[ e\text{-spin} \]
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Pulse sequence

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Pulse sequence

RF
MW2
MW1
Laser
Detector

Operation: Initialize U(t) Map 1 2 ··· Repetitive Readout [RR x60] ··· 60

State:

\[ |0\rangle_e \otimes |\downarrow\rangle_n = \left(a |0\rangle_e + b |1\rangle_e\right) \otimes |\downarrow\rangle_n \]

\[ a |0\rangle_e |\downarrow\rangle_n + b |1\rangle_e |\uparrow\rangle_n \]

\[ |0\rangle_e \otimes (|a|^2 |\downarrow\rangle \langle \downarrow| + |b|^2 |\uparrow\rangle \langle \uparrow|) \]
Improved readout of electron Rabi oscillations
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✓ Result: 10-fold improvement in contrast
  > 2-fold improvement in signal to noise of readout

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✓ Further improvement using 2 nuclear ancillae & concatenated sequence

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Improved readout of electron Rabi oscillations

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Example of useful few-qubit algorithm

L. Jiang, J. Hodges et al, (2009), similar to Al ion clock Wineland group

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Search for a “perfect” hybrid qubit

✓ Remarkable efforts from experiments & material science to theory

✓ Open questions:

Nitrogen-vacancy color centers in diamond is one of 500+ impurities in diamond:
  what about others?
other modern material systems: nanotubes etc?
other useful “hybrids”, e.g. topological qubits?
Hybrid architectures:
combining useful features of different qubits
Hybrid quantum architectures
Hybrid quantum architectures

✓ Pioneering example: quantum optical interface

Non-local coupling of quantum bits by absorbing or emitting a photon in a controlled way

Cirac, Zoller, Mabuchi, Kimble, PRL 78, 3221 (1997)

experiments at Caltech, MPQ
Hybrid quantum architectures

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✓ Broad effort in AMO community:
   single neutral atoms, ions, atomic ensembles, solid-state emitters
   new approaches to q.networks: probabilistic, cluster state techniques etc
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✓ Remarkable new interconnects:
  in optical, microwave, mechanical domains
Quantum interfaces based on photonic crystal cavities

$|E|^2$

$Q = \tau \omega$

$\tau =$ decay time

$V =$ mode

volume
Quantum interfaces based on photonic crystal cavities

\[ |E|^2 \]

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\[ \tau = \text{decay time} \]

\[ V = \text{mode volume} \]
Quantum interfaces based on photonic crystal cavities

Photonic crystals can localize light into extremely small volumes $V \sim (\lambda/n)^3$ with quality factors $Q \sim 10^6$; large $Q/V$ ⇒ cavity QED in strong coupling regime in Si, Ga-based PCCs
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)
Quantum interfaces based on PCs: recent advances

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• Challenge: extend these techniques to other qubits with better coherence properties, other materials, hybrid qubit/cavity systems, e.g. diamond+GaP cavities
Extension to nanoscale using plasmonic systems

✓ Sub-wavelength localization and guiding electromagnetic field on conducting wires results in strong coupling of single atoms to plasmon field
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✓ Example: proximal atom emission guided almost completely into the wire accompanied by large enhancement
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✓ Example: proximal atom emission guided almost completely into the wire accompanied by large enhancement

✓ Realization: atoms = single CdSe q.dots, NVs in nanocrystals efficiently coupled to silver nanowires (~100 nm)


✓ Current efforts:
  hybrid optoplasmonic systems to avoid losses
    e.g. K.Vahala group, Nature (2009)
  on-chip detection, nano-scale “dark” optical circuits
    A.Folk, F. Koppens et al, Nature Physics, in press
  application to single photon collection, switches, transistors
Nano-mechanical quantum spin transducers

Quantum nanomechanics
M. Aspelmeyer, D. Bouwmeester, J. Harris, T. Kippenberg, K. Schwab
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displacement

magnetic dipole
Coupling of single spin to mechanical motion in magnetized tip

- Zeeman shift due to one quantum of motion @ h=30 nm distance ~ 100 KHz exceed spin $T_2$, motional decoherence of nanomechanical system
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$$H_S = H_{NV} + \hbar \omega_r a^\dagger a + \hbar \lambda (a + a^\dagger) S_z$$

✓ “Cavity QED” with mechanical motion
✓ New possibilities:
  cooling, quanta by quanta engineering “arbitrary” motional states, mapping spin into motion, amplifying spin signals using charged tips…

Quantum nanomechanics
M. Aspelmeyer, D. Bouwmeester, J.Harris, T. Kippenberg, K.Schwab
Remote spin coupling via NEMS data bus

✓ Mapping spin to mechanical motion of magnetic, charged tip can be used to “amplify” spin signals

P. Rabl et al., collaboration with J. Harris, P. Zoller’s groups
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100kHz coupling strength over 10s of µm distances

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✓ Applications: remote coupling between spins, coupling to ions, other charged qubits
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Search for “ideal” quantum bus is not over!

P.Rabl et al, collaboration with J.Harris, P.Zoller’s group
Outlook: potential applications of hybrid systems
Quantum communication: long-distance challenge

- High quality entanglement and QKD over >1000 km channels
Quantum communication: long-distance challenge

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Alice

Bob

○ ○ ○ ○ ○ ○ ○ ○ ○ ○ ○

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  • intermediate nodes
Quantum communication: long-distance challenge

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  • entangle nearby nodes in parallel, use memory to store entanglement
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The idea of quantum repeater:
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• entangle nearby nodes in parallel, use memory to store entanglement
• purify entanglement, connect nodes by Bell measurement.
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![Diagram showing entanglement process between Alice and Bob through intermediate nodes.]

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Briegel et al. PRL 81, 5932 (1998)
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  • Efficient light-matter interface, few-qubit memory, logic has been demonstrated: need to combine them all, interface with telecom
  • Current protocols: polynomial scaling but slow (one bit/second level), need new approaches for efficient use of resources, time

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Need new, more efficient protocols & architectures
Metrology & sensing

✓ Quantum coherence, logic, entanglement for metrology
Metrology & sensing

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• Better clocks: one of the early motivation to study entanglement in AMO systems
Metrology & sensing

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• New avenues:
  use solid-state systems
  extend to new domains, e.g. nanometer-scale sensing
Example: application to nanoscale magnetic sensing

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

J. Maze et al, Nature (2008),
Example: application to nanoscale magnetic sensing

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• Current efforts:
development of AFM-based scanning sensors far-field nonlinear optical spin imaging at nanoscales use few spin entangled states for sensing
Outlook: hybrid experimental technologies

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All require atom trapping within 100 nm of solid-state surface

Challenges: noise, patch potentials, van der Wal interaction ...
Toward nanoscale interface for isolated atoms
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✓ Micro- and nanophotonic systems for trapping of isolated atoms
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• Current experiments with atoms - micron localization:
  e.g. atoms near pulled fiber (Tokyo, Maintz),
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M.Bajcsy et al, PRL (2009)
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- Strong blue “shield” for nanotip => can trap 50 nm from surfaces

D.Chang et al., collaboration with Peter Zoller, Vladan Vuletic, Hongkun Park
Also: plasmon tweezer work @ ICFO (Barcelona), atoms around nanotubes ideas (Hau)
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Such techniques will be critical for combining isolated atoms, molecules with solid-state quantum systems
New field of low-energy quantum science
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  condensed matter physics
  nanoscience, chemistry
  photonic & electrical device engineering
  quantum information science…
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  controlled manipulation of quantum mechanical phenomena
  search for new quantum states of matter
  potential applications of controlled quantum phenomena
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These are long-term, “high risk” projects: stable funding is critical!