Quantum control of individual electron and nuclear spins in diamond lattice

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Today’s talk

• Introduction: quantum control from AMO to solid-state

• Quantum control of single electron spins
  ✓ System: electron spin in Nitrogen Vacancy (NV) center in diamond
  ✓ Understanding mesoscopic environment of single electron spin: $^{13}$C nuclei as a leading decoherence source

• Quantum control of single nuclear spins
  ✓ Single nuclear spin addressing via quantum back-action from electron
  ✓ Coherent coupling of electron and nuclear spin qubits
  ✓ NMR on a single spin

• Scaling up using quantum optics
  ✓ New ideas and new tools
Quantum control: from AMO to solid state

- Solid-state quantum systems
  - New opportunities:
    - tight confinement, fast operations
    - strong interactions
    - “easy” entanglement

- Electron spin as quantum bit
  - Promising, stable qubit candidate
  - We show that interaction with lattice nuclei determine coherence properties and that (nuclear spin) environment can be understood, controlled and utilized as a resource
System: NV color center in high-purity diamond

“Nature’s own trapped molecular ion”

Optical properties
- Sharp zero-phonon emission line @ 637 nm
  + phonon sidebands 650-730 nm
- Can be excited either by 637 nm or 532 nm

Ground state properties
- non-zero electronic spin (S=1)
- microwave transition:
  zero-field splitting $\Delta=2.88$ GHz
- detectable via state-selective fluorescence

Early work:
S. Rand, N. Manson
Experimental probing of single centers

- Scanning confocal microscope image
- Single photon source: ~100,000 cts/sec (Paris, Munich,..)
Preparation and probing of single spins

Optical excitation:
- State selective fluorescence
- Electron spins polarization (>90%)

...enables
- Manipulation spin states using microwave ESR
- Detection using spin-dependent fluorescence

2.88 GHz at room temperature
Rabi oscillations of single electron spin

First experiments
F. Jelezko, J. Wrachtrup (Stuttgart)

- Contrast limited by competition of optical pumping and shelving effects (improves with efficient collection)
- Calibrates measurement efficiency for other data
Single spin coherence via Ramsey spectroscopy

✓ “Classic” probe of coherence properties

✓ Overall decay on a 1-2 μs scale
✓ “Beating” of modulation components
✓ Each center is different!

Signatures of complex, non-Markovian environment: can we understand, control it?
Mesoscopic environment of NV center

✓ Stiff, mostly spinless $^{12}$C lattice
✓ Possible contributors to dephasing:
  • Contact hyperfine interaction:
    single N nuclear spin (I=1)
  • Coupling to remote spins, e.g.:
    $^{13}$C nuclear spins (few percent)
    N (impurity) electron spins:
    need pure samples

✓ Theory: mesoscopic spin bath

\[ H = g_0 S_z I_z^N + \sum_{j} g_j S_z I_z^j. \]

- local (N)
- non-local
  \[ g_j \sim \frac{1}{r_j^3} \]
  effective “nuclear” field
Dephasing of electron spin by mesoscopic environment

- High “nuclear temperature” $\Rightarrow$ random nuclear field
  
  $B_{\text{nuc}} \sim g_0 I_z^N + \sum_j g_j I_n^j$

- Effect of surrounding spins:
  - Few spins $\Rightarrow$ few modulation frequencies
  - Many spins $\Rightarrow$ dephasing

- Dephasing: a large number (1000s) of nearby spins contribute
  
  $T_2^* = 2\left(\sum_j |g_j|^2\right)^{-1}$

- Nuclear spins evolve slowly:
  - long correlation time of the environment

for 1.1% abundance $^{13}$C
Probing single electron coherence via spin echo

- Typical echo decay ...

The spin echo signal is only sensitive to changes in the environment which happen faster than $\tau$

...results in much longer coherence

a tool to understand the dynamics of the local environment
Single spin echo in magnetic field

✓ Echo envelope on longer time scale...

...periodically collapses and revives

✓ Big effect: $T_2 > 200 \mu s \sim 200 \, T_2^*$!

✓ Suggests periodic dynamics of electron environment
Dynamics of spin environment in B field

Main reason for echo evolution: changes in $B_{nuc}$

$$H = g_0 S_z I_z^N + \sum_j g_j S_z I_{nj}^j + \sum_j \Omega I_n^j$$

Nuclear Larmor evolution leads to
⇒ de-correlation of $B_{nuc}$
⇒ re-phasing after one Larmor period

Echo revives when waiting interval matches Larmor period!

L. Childress, M.G.Dutt, J.Taylor et al, Science, in press
A picture of single electron environment: $^{13}$C nuclei in diamond lattice

Environment as a resource: can we address and use individual isolated $^{13}$C nuclei in diamond lattice?
Coupled electron-nuclear system: more detailed view

✓ Hyperfine interaction of electron with single nuclear spin $I^{(j)}$

$$V^{(j)} = -\mu_e \mu_n \frac{8\pi |\psi_e(r_j)|^2}{3} \mathbf{S} \cdot \mathbf{I}^{(j)} + \left\langle \frac{\mu_e \mu_n}{r_j^3} \left( \mathbf{S} \cdot \mathbf{I}^{(j)} - 3(n_j \cdot \mathbf{S})(n_j \cdot \mathbf{I}^{(j)}) \right) \right\rangle$$

✓ In weak B field electron dynamics is conditional upon nuclear state and vice versa => entanglement

✓ Echo signal resulting from single nucleus

Larmor collapse and revival

$\langle S' \rangle$

Fast modulation (hyperfine)

…displays coherent electron-nuclear spin dynamics

✓ Many spins in bath $\Rightarrow \langle S \rangle = \prod_j S_j$ Decoherence!
Proximal nuclei are special: back-action from electron

Atomic physics of spin bath

- Two effects of electron on proximal nuclei due to hyperfine field:
  - Larger hyperfine splitting
  - Enhanced Larmor frequency

- Hyperfine coupling enhances nuclear magnetic moment
  - Hyperfine interaction mixes electronic and nuclear states: response to B-field given by g-tensor

\[
\mu_{\text{eff}} \sim \mu_{\text{nuc}} + \frac{\langle V(r_j) \rangle}{\Delta} \times \mu_e
\]

- Substantial enhancement even for weak mixing since \( \mu_e \sim 10^3 \mu_{\text{nuc}} \)

Proximal nuclei are very special: they precess faster
Coherent dynamics involving individual nuclear spins

- Each NV center has its own, specific dynamics
- Most display periodic entanglement and disentanglement with (some) isolated nuclear spin(s)

- Larmor envelope
- Fast hyperfine modulation

L. Childress, M.G. Dutt, J. Taylor et al
Coupling to proximal $^{13}$C: nuclei-resolving microscope

- Echo modulation frequencies for different centers

- Level mixing and $\mu$ enhancement depend on relative distance

- ... and B-field orientation relative to S-I axis!

- Confirms the model

- Allows to determine coupling constants for individual nuclear spins, information on positions
Coherent, deterministic coupling to isolated single nuclear spins in diamond lattice

✓ Addressing of well-defined, isolated nuclear spins possible (up to 3)
✓ Coherent, controllable two-qubit (or few qubit!) system

Watching single nuclear spin precession

✓ Pulse sequence to map qubits between electron to nuclear spin

MW

\[ \frac{\pi}{\omega_{j,1}} \quad \frac{\pi}{\omega_{j,0}} \]

\[ \frac{\pi}{2} \quad \frac{\pi}{2} \]

✓ Example: single nuclear spin

polarize  polarize  dynamics

nuclear polarization  Larmor precession  mapping to electron

• NMR on single, isolated nuclear spin!
Nuclear spin as robust quantum memory

✓ Second long coherence times are expected for isolated nuclear spins!
✓ How well is $^{13}$C really isolated (e.g. from nearby electron)?
Example: cycling electron with green light during nuclear precession

✓ Isolated nuclear qubit: potential for excellent quantum memory
Outlook: useful quantum processors from two qubits

✓ Electron entanglement via photon scattering & single photon interference
✓ Deterministic quantum gates between remote nuclei via electron-nuclear coupling: high fidelity and rates for modest collection efficiency
✓ Operations between any pairs can be performed simultaneously: purely optical scaling for quantum communication & computation

Theory:
L. Duan, C. Monroe (ions)
L. Childress, J. Taylor, A. Sorensen. MDL PRL 06, quantum repeaters
L. Jiang et al, (06) deterministic computation
Summary: single spin environment can be understood, controlled and utilized

✓ Coherent manipulation of single electron spin using AMO techniques

✓ Understanding mesoscopic environment of single electron via spin echo

✓ Coherent manipulation of individual proximal nuclei: single spin NMR

✓ Quantum optical techniques for wiring up multi-qubit systems

A new frontier on the interface of AMO and cond-mat physics