Controlling individual nuclear spins in diamond: from coherence to scalability

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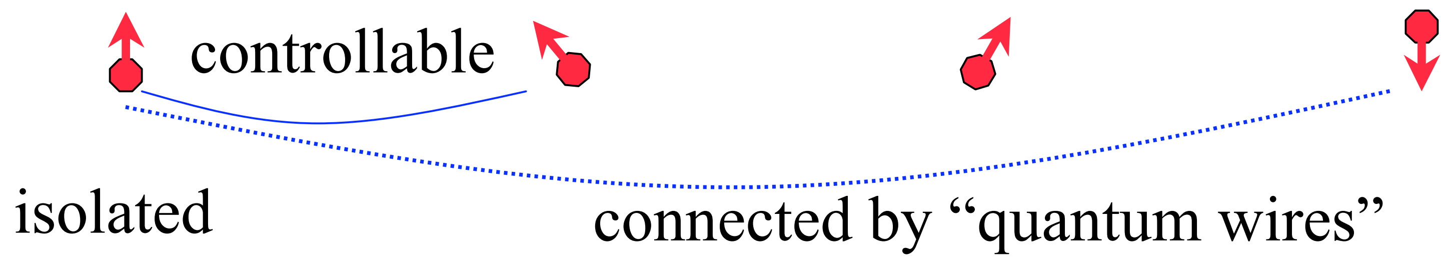
Presented at the PITP/SpinAps Asilomar Conference in June 2007

Building scalable quantum information systems: an outstanding challenge in science and engineering

✓Quantum bits and quantum wires



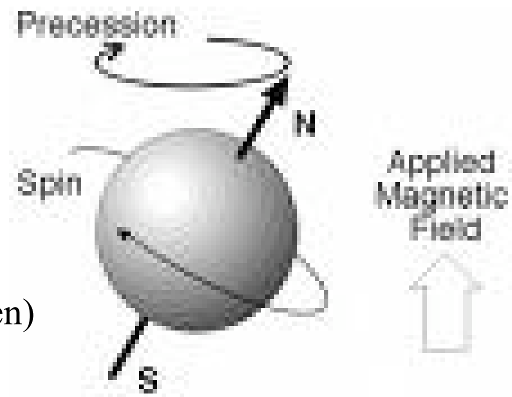
- Solid-state quantum systems

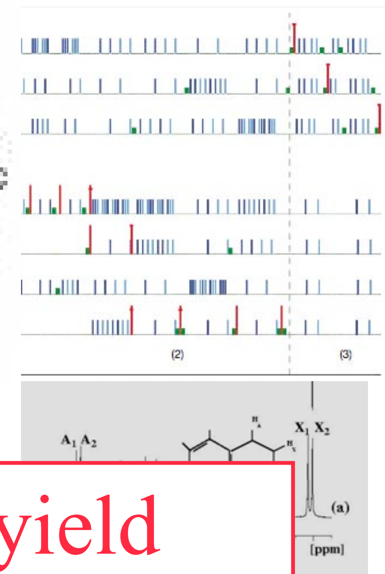
✓Challenge of isolation:
quantum control in complex solid-state environment

This talk: environment as a resource yields - stable,controllable quantum bits

Spins and photons: best of both worlds

✓Magnetic resonance





Dramatic proof-of-principle NMR quantum computation (e.g. Chuang, Cory, Laflamme, Vandersypen)

• Hard to scale:

no individual initialization, measurements,

Would like to combine the advantages to yield scalable, robust systems

✓Single photon quantum optics

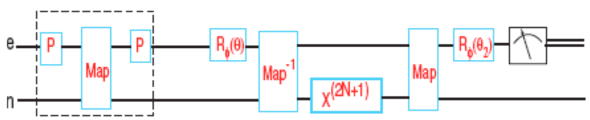
Pure single photon qubits, entangled pairs, ideal for communication, many dramatic demonstrations e.g. teleportation, KLM…

• Hard to scale:

no memory

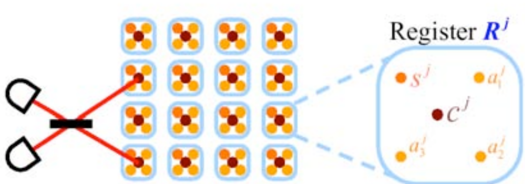
photons do not interact

Today's talk: novel hybrid approach



✓ Electron-nuclear register: key elements

quantum operations with electron and nuclear qubits
coherent coupling of individual nuclei
exceptional isolation: coherence properties of nuclear qubits

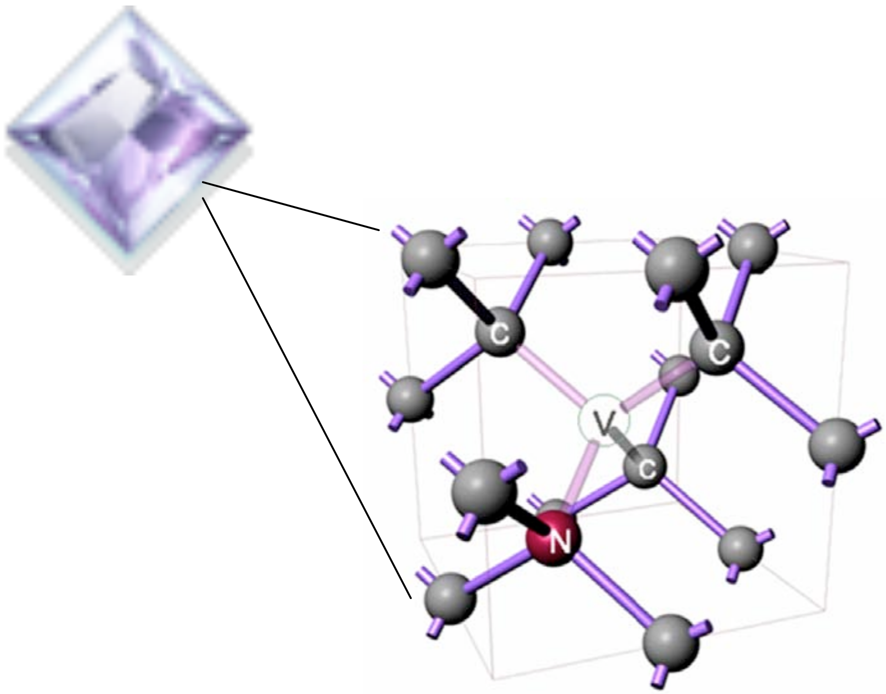


✓ Scaling up electron-nuclear registers with photons:

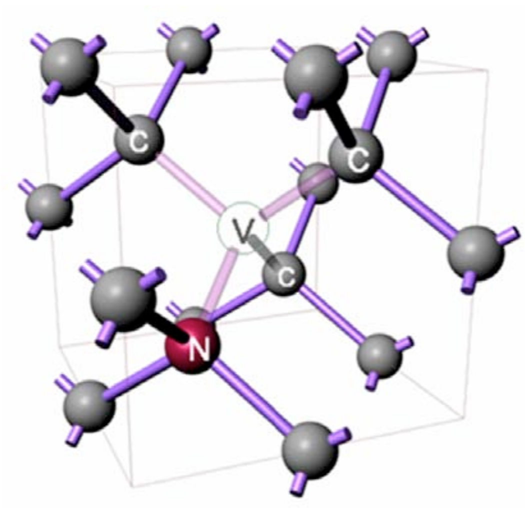
measurement-based optical connects
deterministic, measurement-based network approach

✓ Outlook

“Diamond Age”:
controlling single electrons and single nuclei

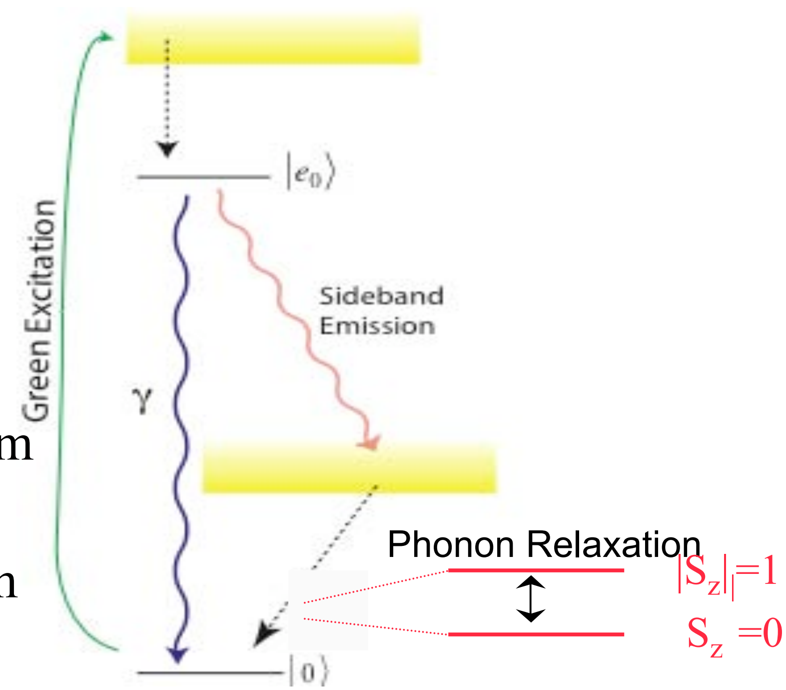


System: NV color center in high-purity diamond



“Nature’s own trapped molecular ion”

natural or implanted



Optical properties

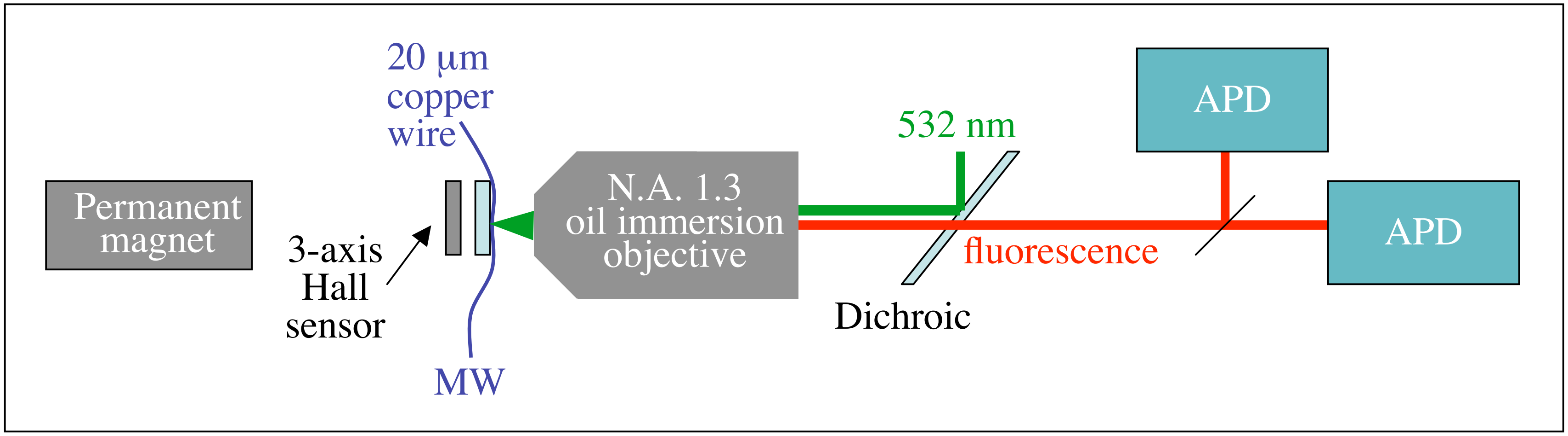
- Sharp zero-phonon emission line @ 637 nm
  + phonon sidebands 650-730 nm
- Can be excited either by 637 nm or 532 nm

Ground state properties

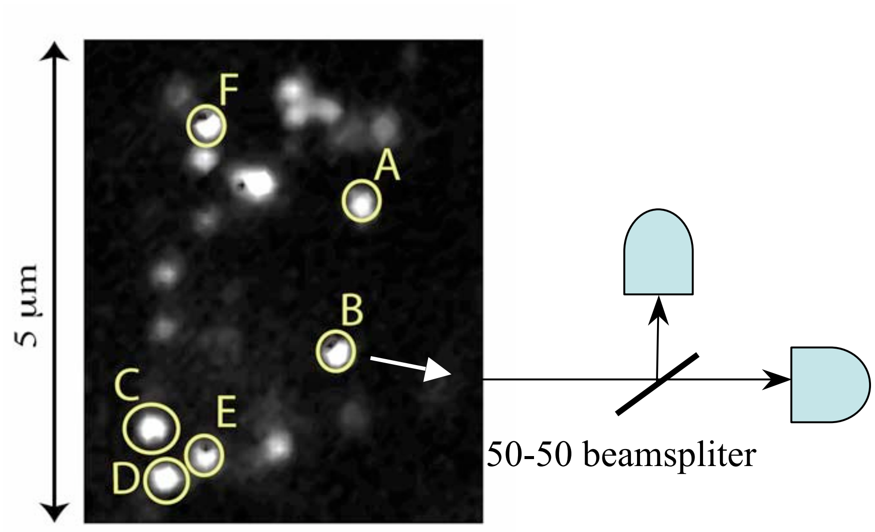
- non-zero electronic spin (S=1)
- microwave transition:
  zero-field splitting Δ=2.88 GHz

Early work:
S.Rand, N.Manson

Experimental isolation of single centers

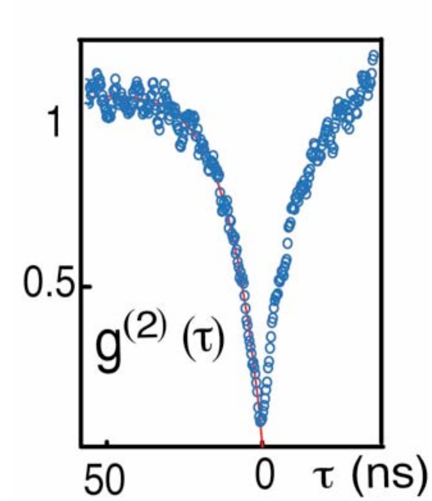


✓Scanning confocal microscope image



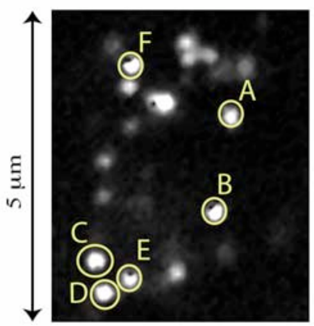
✓Single photon source:

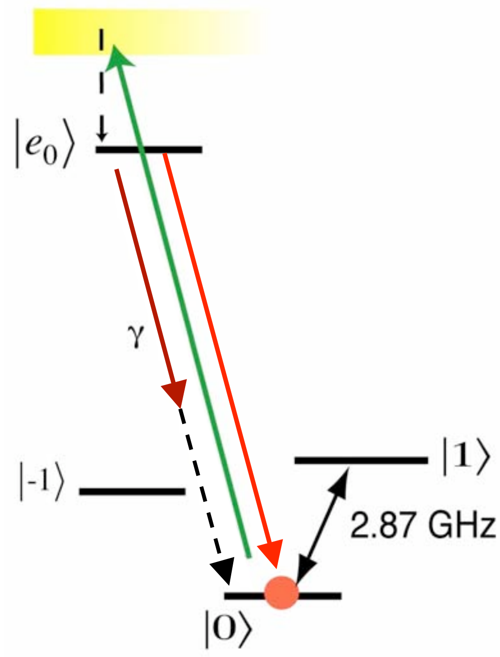
~100,000 cts/sec (Paris, Munich,..)

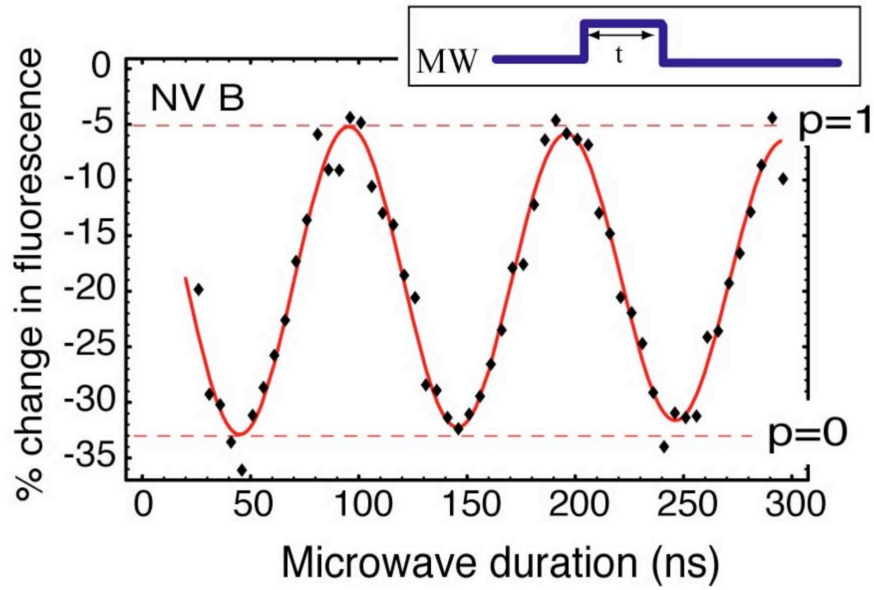


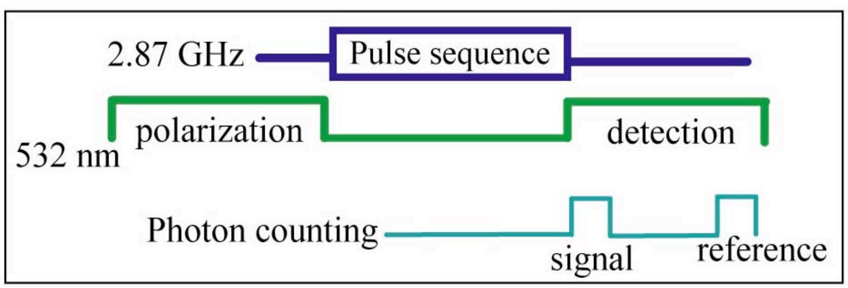
Rabi oscillations of single electron spin

Use light to isolated, polarize, readout electron spin state at room T









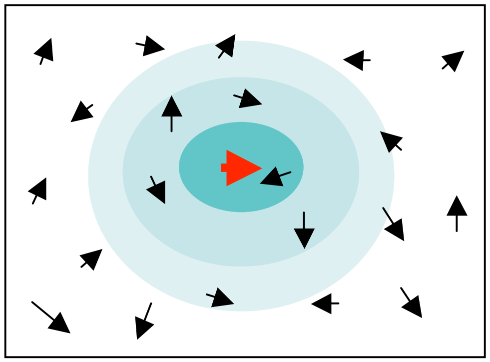
✓Pioneering work

F.Jelezko, J.Wrachtrup (Stuttgart)

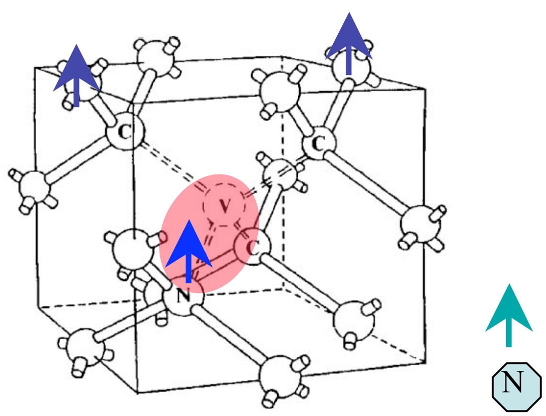
Recent work by D.Awschlom (UCSB)

✓Electron precession decay time (average over many runs): $T_2^* \sim 1\mu s$

Understanding local environment of single electron spins



Mesoscopic environment of NV center: sensitive probing via electron spin



✓Stiff, mostly spinless ^{12}C lattice

✓Possible contributors:

- Contact hyperfine interaction:
  single N nuclear spin (I=1)

- Coupling to remote spins, e.g.:
  C^{13} nuclear spins (few percent)
  Impurity (N) electron spins:
  need pure samples

✓Theory: mesoscopic "spin bath"

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

local (N) non-local

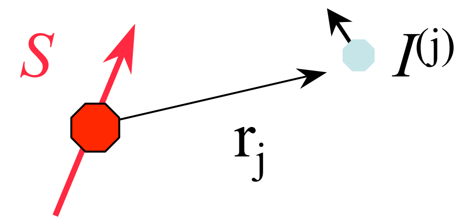
"nuclear" field

✓Key observation: nuclear spins are extremely coherent,
environment can be a very useful resource

Presented at the PITP/SpinAps Asilomar Conference in June 2007
Brought to you by PITP (www.pitp.phas.ubc.ca)

Dynamics of coupled electron and nuclear spins

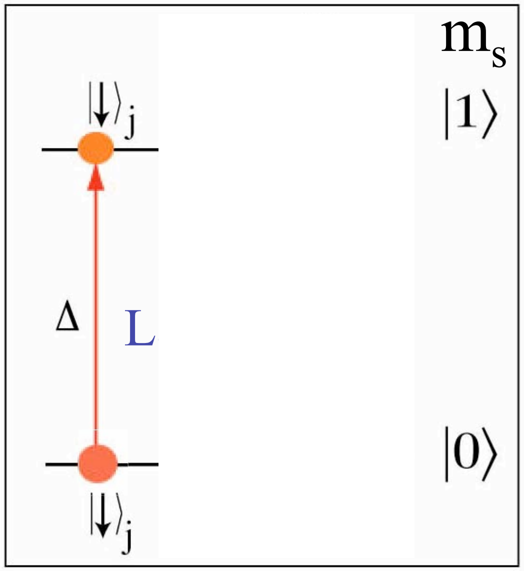
✓Hyperfine interaction of electron with single nuclear spin $I^{(j)}$



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

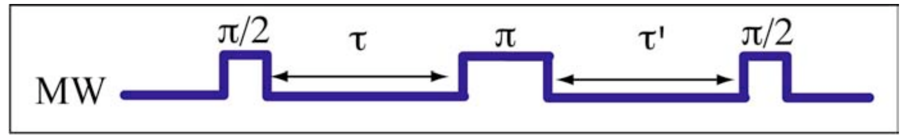
✓m_s =1 electron causes hyperfine splitting of nuclear states
✓m_s = 0 electron external field causes Larmor precession

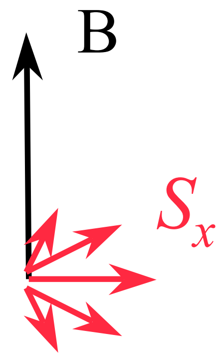
✓Electron-nuclear entanglement dynamics:
in weak B field electron dynamics is conditional
upon nuclear state and vice versa



✓Electron spin: sensitive probe of local environment..
… but typically interacts with a large bath of nuclei
which results in decoherence

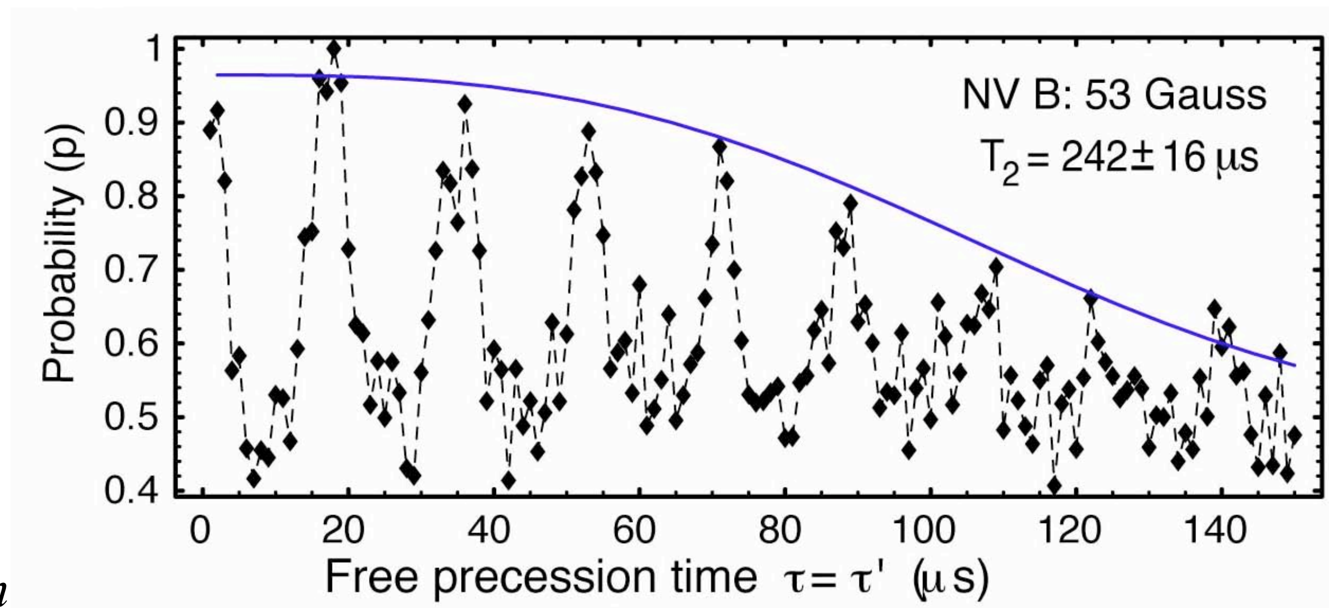
Probing single electron environment via spin echo





E.Hahn 1950s

✓Typical echo we observe



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

…periodic collapses and revives

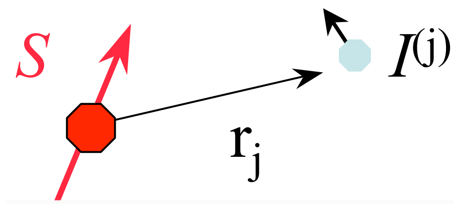
✓Big effect: T_2 >200 μs ~ 200 T_2^* : environment has long memory

✓ Periodic modulation due to Larmor precession of bath ^{13}C nuclei

Bulk ESR: Electron Spin Echo Envelope Modulation (W.Mims et al, 70s)

More careful look: proximal nuclei are special

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

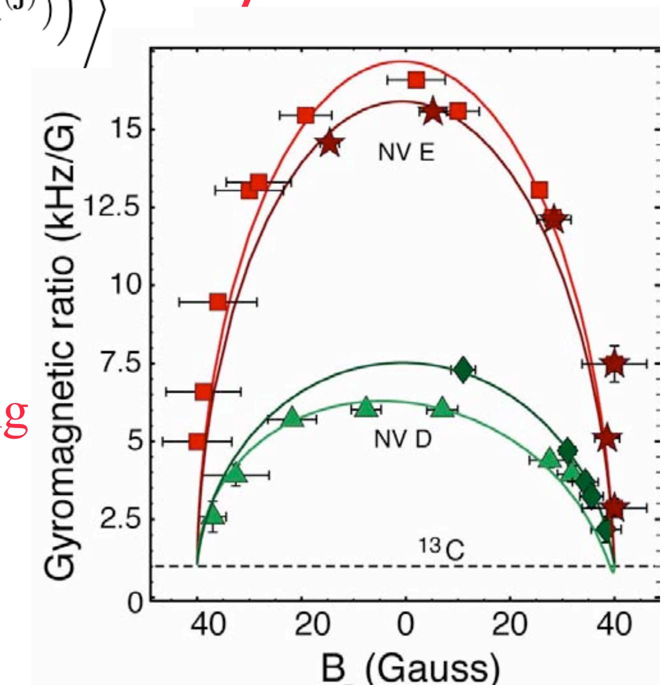


$$V^{(j)} = -\mu_e \mu_n \frac{8\pi|\psi_e(r_j)|^2}{3} \mathbf{S}\cdot\mathbf{I^{(j)}} + \left\langle \frac{\mu_e \mu_n}{\mathbf{r_j^3}} \left(\mathbf{S}\cdot\mathbf{I^{(j)}} - \mathbf{3}(\mathbf{n_j}\cdot\mathbf{S})(\mathbf{n_j}\cdot\mathbf{I^{(j)}})\right)\right\rangle$$

✓ Two effects of electron on proximal nuclei due to hyperfine field:

- larger hyperfine interaction
- enhanced Larmor frequency due to hyperfine mixing

unique "chemical shift"



$$\mu_{\perp}^{eff} \sim \mu_{nuc} + \frac{\langle V(r_j)\rangle}{\Delta} \times \mu_e$$

electron moment

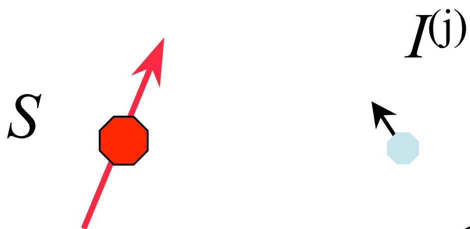
hyperfine level mixing

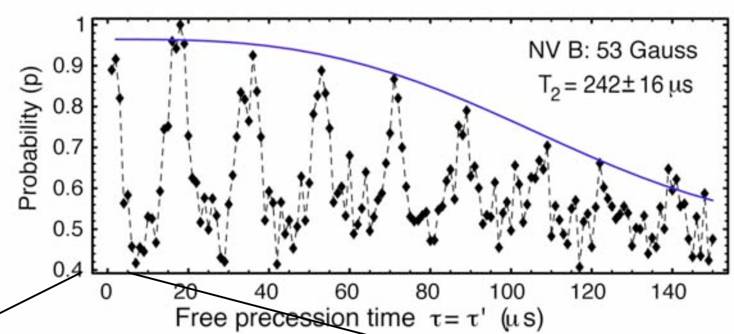
✓Large enhancement since $\mu_e \sim 10^3 \mu_{nuc}$

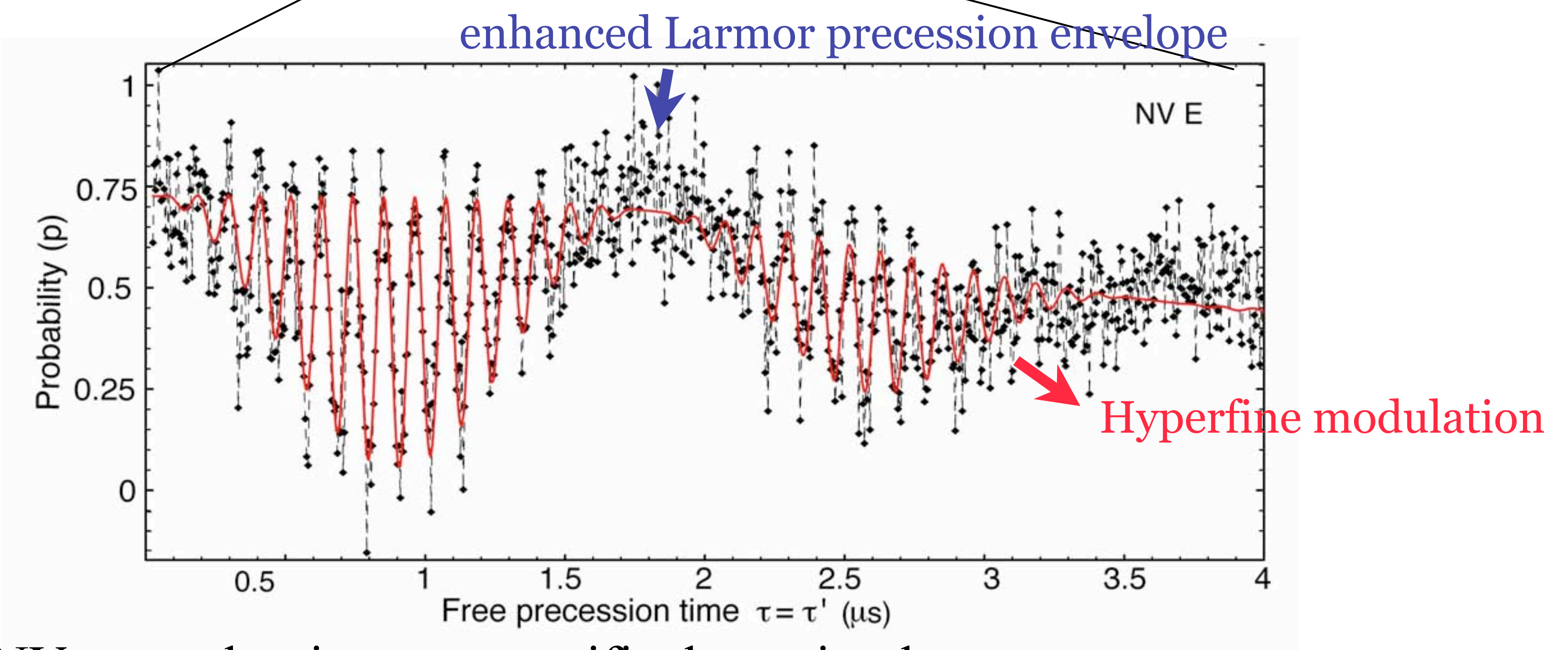
Proximal nuclei can be distinguished from the bath!

Coherent dynamics with individual nuclear spins

✓Electron spin echo at short times





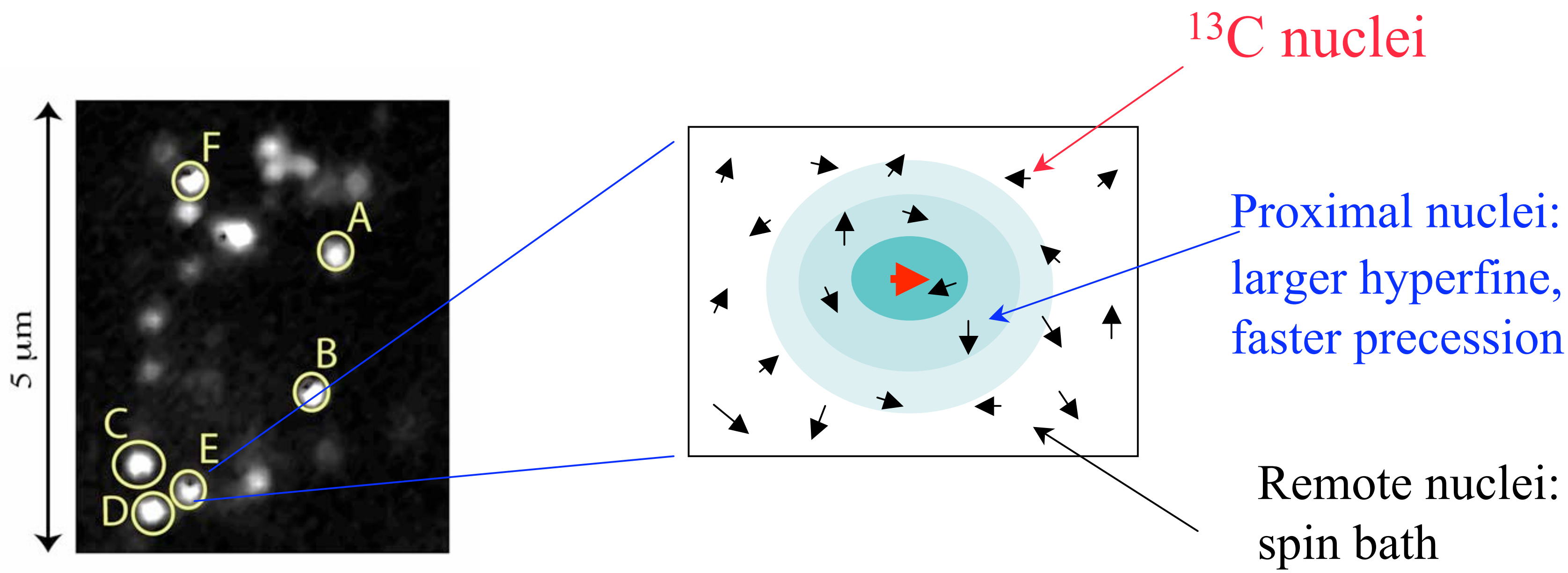


✓Each NV center has its own, specific dynamics, but most display coherent coupling with (some) isolated nuclear spin(s)

L. Childress, M.G.Dutt, J.Taylor, A.Zibrov, F.Jelezko, J.Wrachtrup, P.Hemmer and M.D.L, Science (2006)

Picture of single electron environment

L.Childress et al, Science (2006)



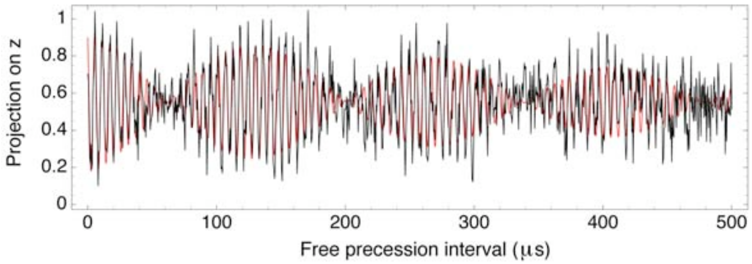
Environment as a resource

✓Idea: electron spin + few proximal nuclei = controllable quantum system "few qubit register"
~a kind of large NMR molecule

✓How to polarize, control, read out individual nuclear spins?

Early ideas: Lloyd, Hemmer, Kilin, Wrachtrup, MDL

Polarizing and measuring individual nuclear spins in diamond lattice

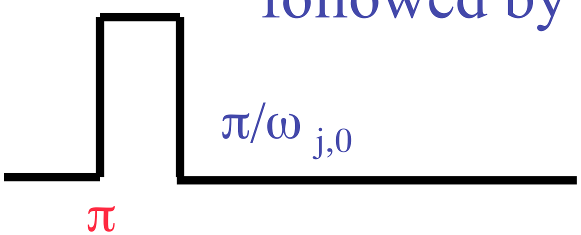


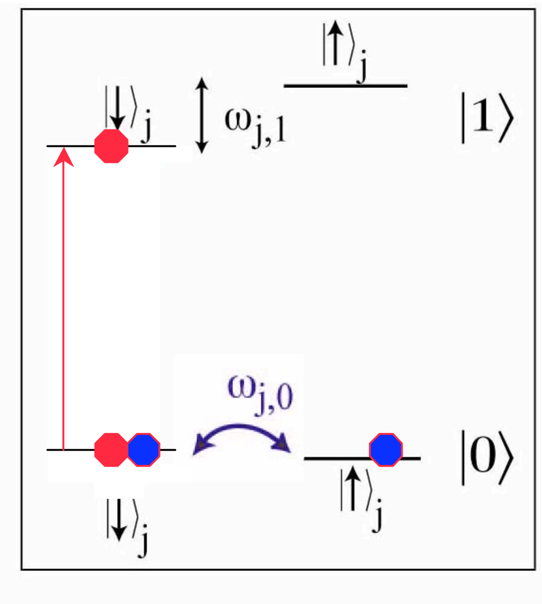
Manipulating individual nuclear spins: the idea

✓Make use of unique hyperfine splitting and chemical shift of proximal nuclei

✓Map qubits between electron to nuclear spin

E.g. selective microwave excitation followed by free precession





✓Can be used for

preparation (polarization)

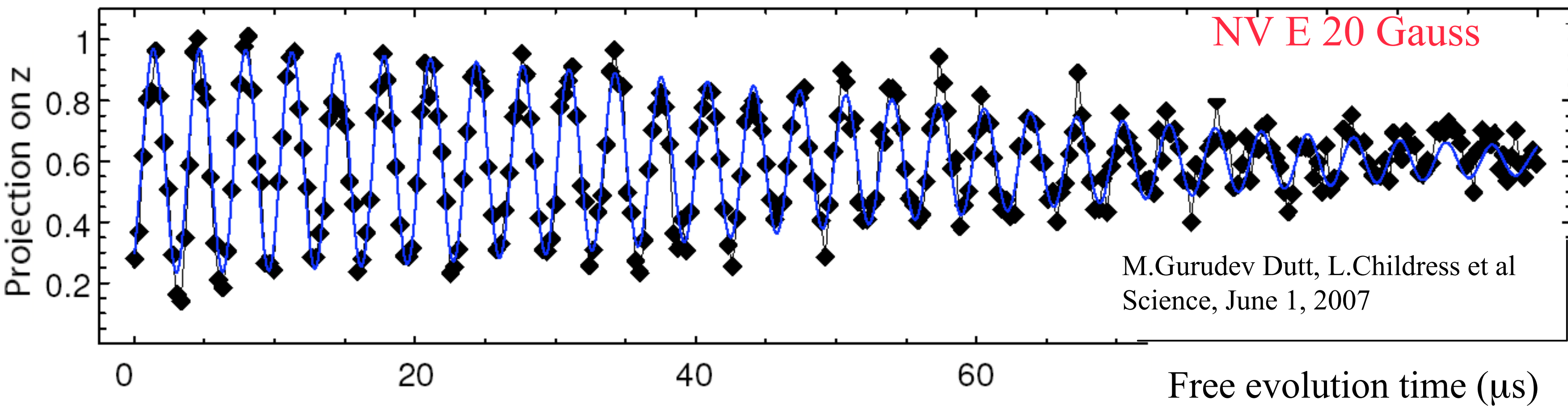
rotation

measurement

of individual nuclear spins

mapping of arbitrary states between electron and nuclei

Example: watching single nuclear spin precession



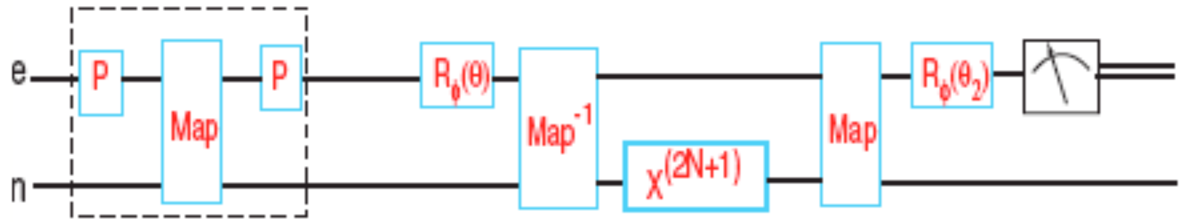
M.Gurudev Dutt, L.Childress et al
Science, June 1, 2007

- NMR on single, isolated nuclear spin!

✓Contrast ~ 70% => Nuclear spin preparation
& readout fidelity F~ 85%

This corresponds to effective nuclear temperature ~ 300 nanoKelvin

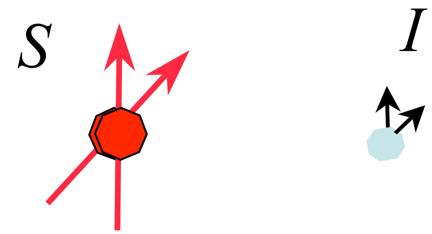
Quantum register based on single electron and few proximal nuclear spins: key elements



Quantum control of coupled electron & nuclear qubits

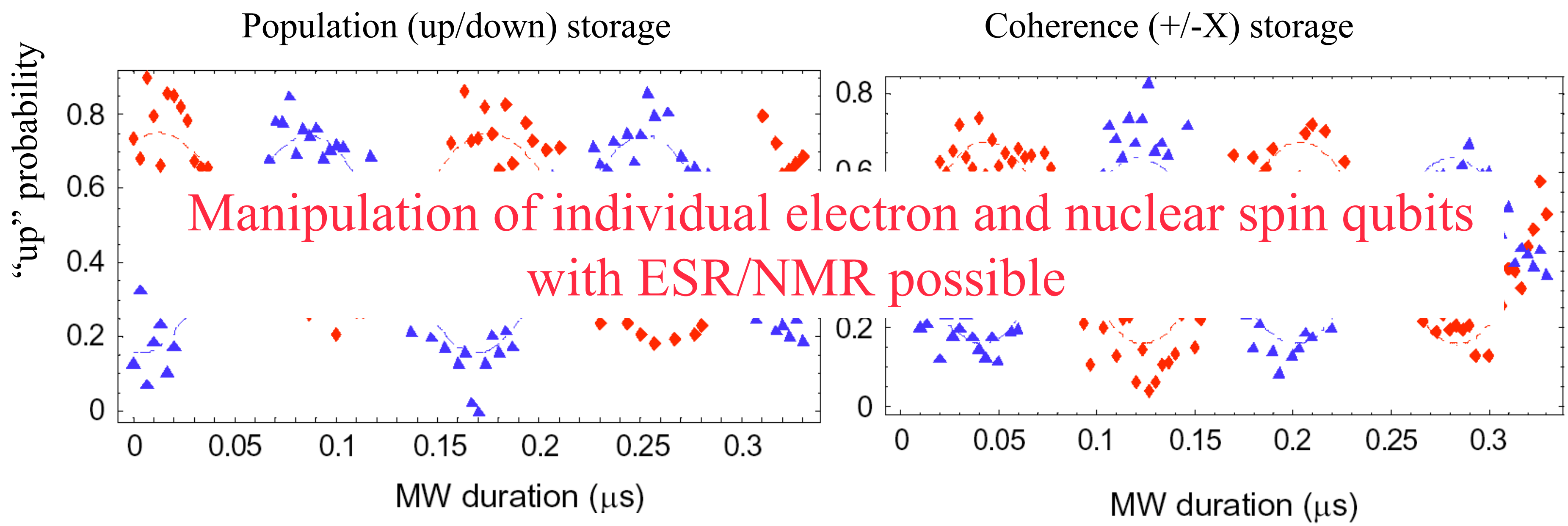
✓Example of quantum operation: storage of arbitrary electron state

MAP



M.Gurudev Dutt, L.Childress et al. (2007)

✓Probe: electron Rabi oscillations following storage and retrieval cycle



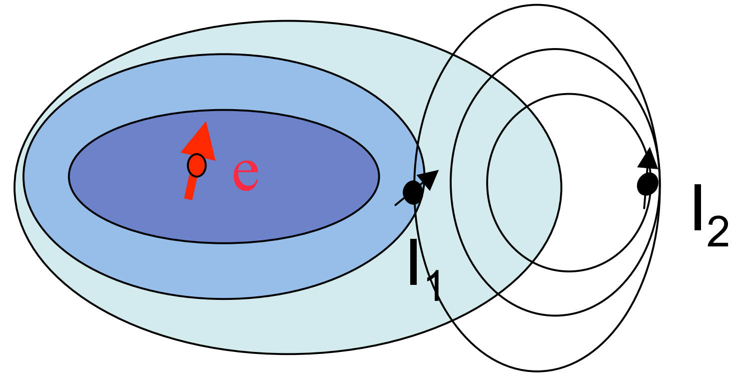
Manipulation of individual electron and nuclear spin qubits with ESR/NMR possible

✓Average storage and retrieval fidelity F=0.75+-0.02 > 2/3

Coherent coupling between nuclear spins qubits

✓Interaction between ^{13}C nuclear spins

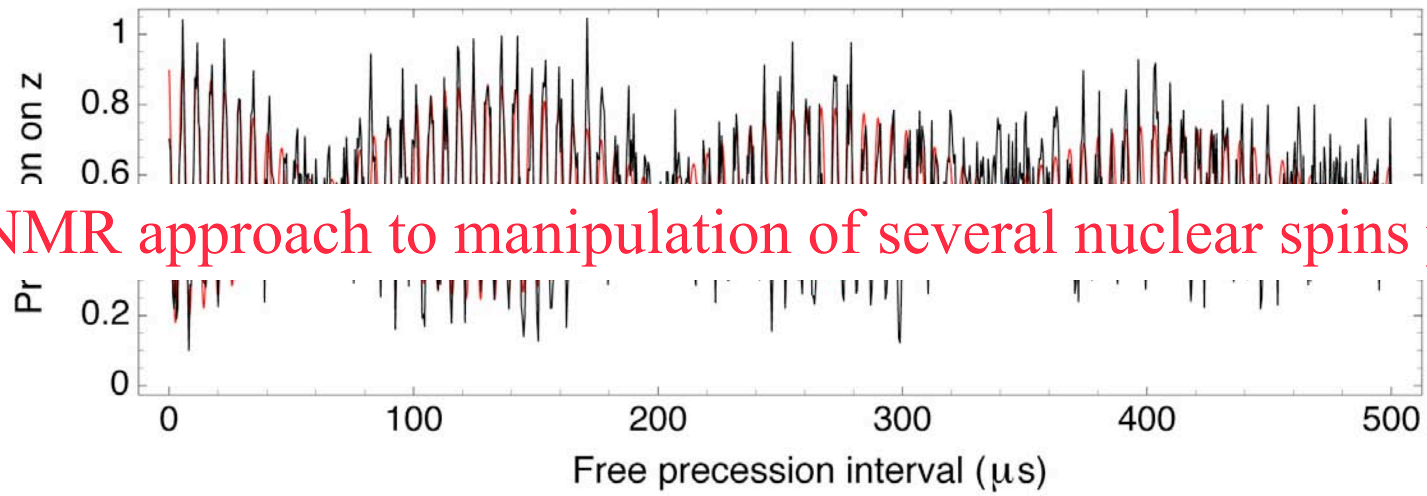
$$H_{12} = \omega_L^1 I_z^{(1)} + \omega_L^2 I_z^{(2)} + \boldsymbol{I}^{(1)} \cdot \boldsymbol{\beta}^{(12)} \cdot \boldsymbol{I}^{(2)}$$



✓Zeeman energies different: ZZ interaction

✓Interaction enhanced by proximal electron

✓Observation: I_1 nuclear spin precession at long times



NMR approach to manipulation of several nuclear spins possible

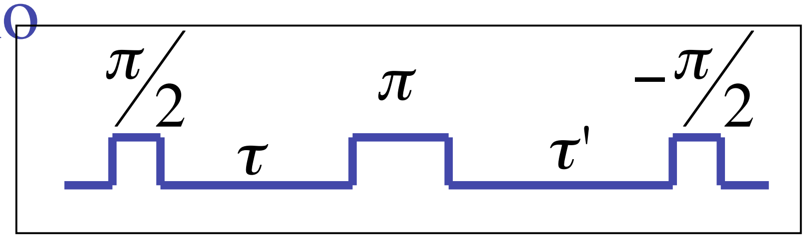
…modulated due to coherent interaction with another nuclear spin (I_2),

✓Modulation rate controlled e.g. by B field orientation

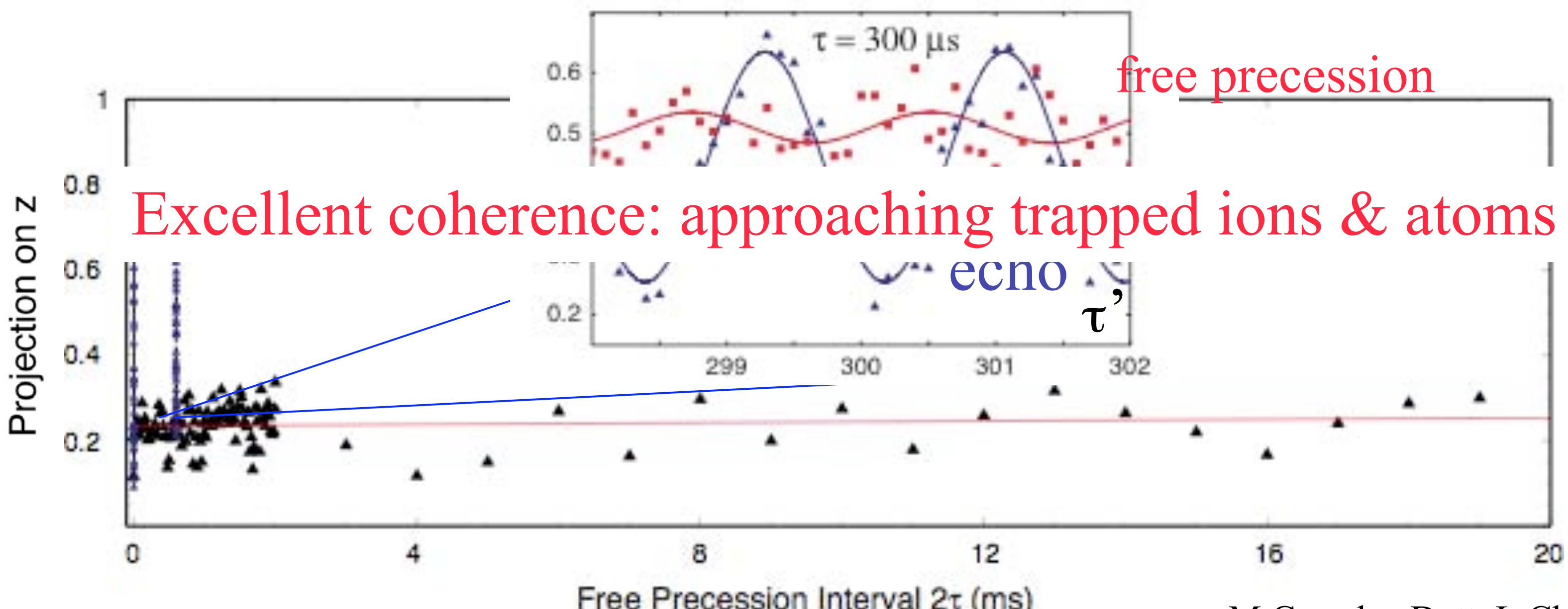
Coherence properties of individual nuclear spins

- ✓ Single nuclear spin $T_2^* = 500 \pm 30\ \mu s$ (longest we've seen)
  Dephasing consistent with being due to (bulk) nuclear spin bath

Decoupling single nuclei: spin-echo



✓Effective NMR sequence
(*with electron's help)



Excellent coherence: approaching trapped ions & atoms

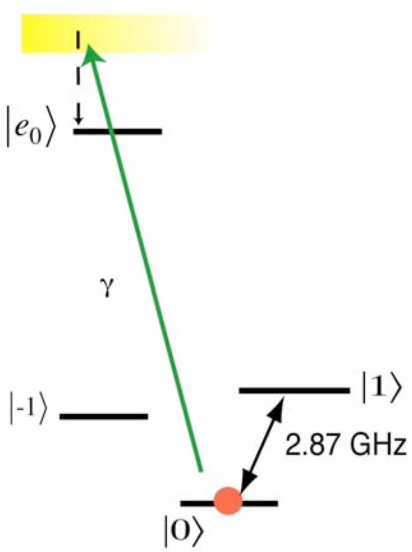
M.Gurudev Dutt, L.Childress et al. Science 2007)

✓Effective decoupling from bulk nuclei:
$T_2 >> 20$ ms … potentially seconds at room T!

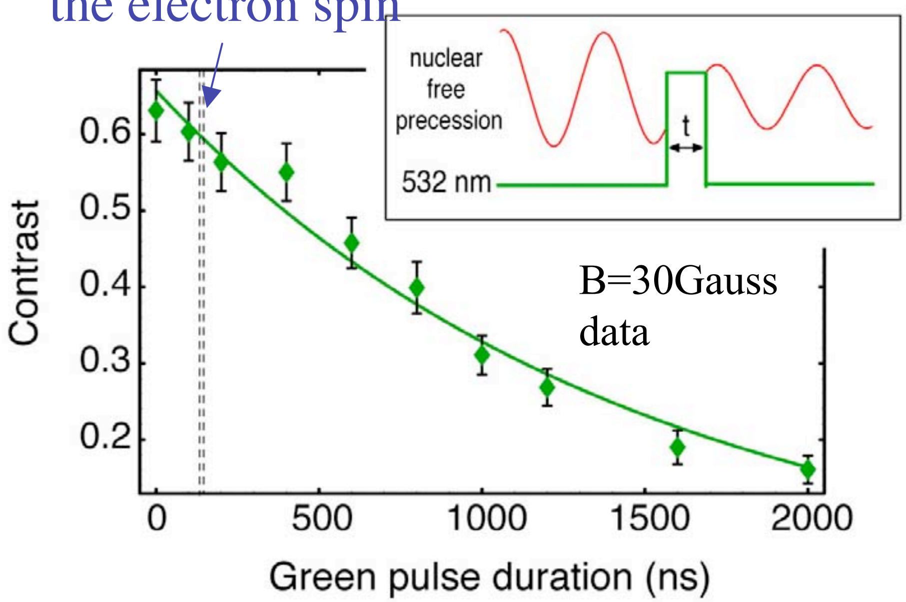
Independent qubit control: isolation of nuclear spins

- ✓Dipolar couplings can be turned off via NMR-type techniques
- ✓How well is ^{13}C isolated during optical excitation of e spin?

Example: interrogating electron with light during nuclear precession



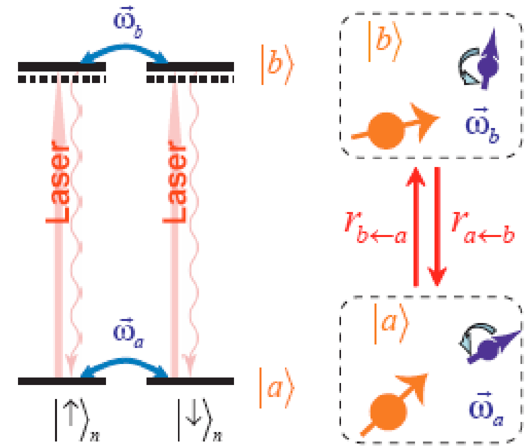
Sufficient light to polarize the electron spin



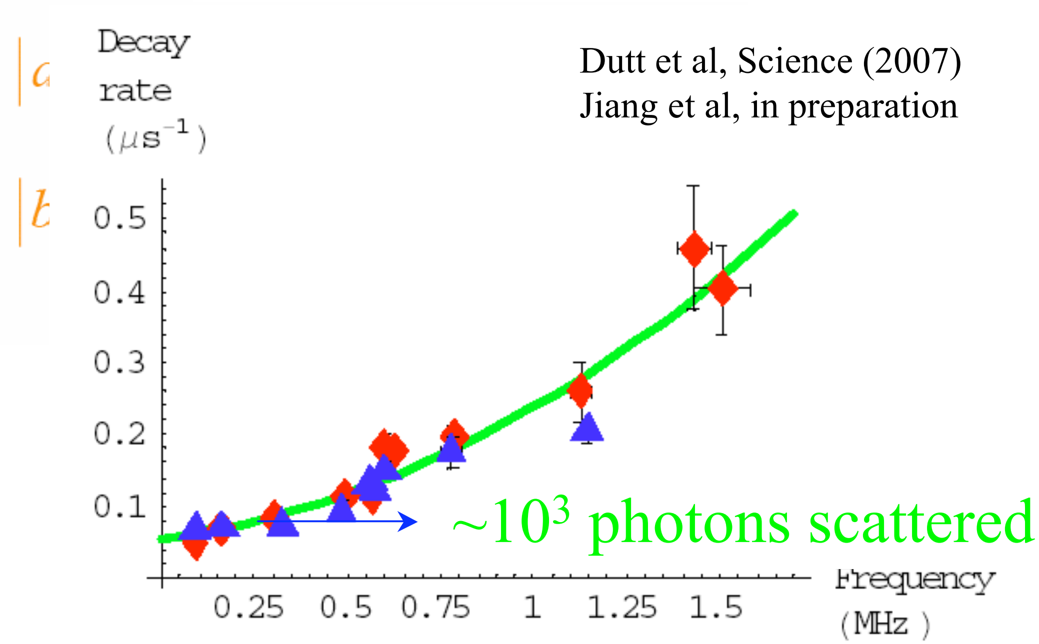
✓Nuclear qubits survive many electron pumping cycles: why?

Isolating nuclear spin via motional averaging

✓Origin: electron state dependant Larmor precession $\Delta\omega = \omega_a - \omega_b$



✓Physics: random fast jumps at rate τ^{-1} result in nuclei dephase at $\Gamma \sim \Delta\omega^2\tau$



Dutt et al, Science (2007)
Jiang et al, in preparation

✓Result: "motional averaging" of decay for $\Delta\omega\tau << 1$

✓ Γ->0 by reducing B field ($\Delta\omega$~B)

✓Independent control of electron & nuclear qubits possible

✓Further improvements: e.g. sweet spots, hiding in remote nuclei …

Electron-nuclear spin registers: summary

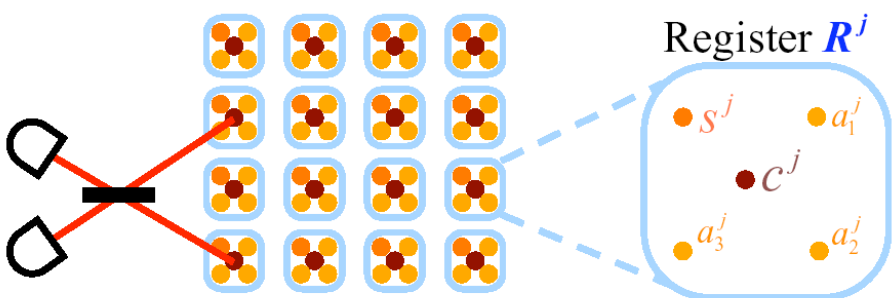
Dutt et al, Science (2007)

✓Key results:

- ✓ Isolated nuclear qubits with excellent coherence properties
- ✓ Few-qubit systems (“registers”) from one electron + several proximal nuclei
- ✓ Robust electron-nuclear and nuclear-nuclear operations via NMR & ESR
- ✓ Isolation of nuclear qubits during optical preparation & readout

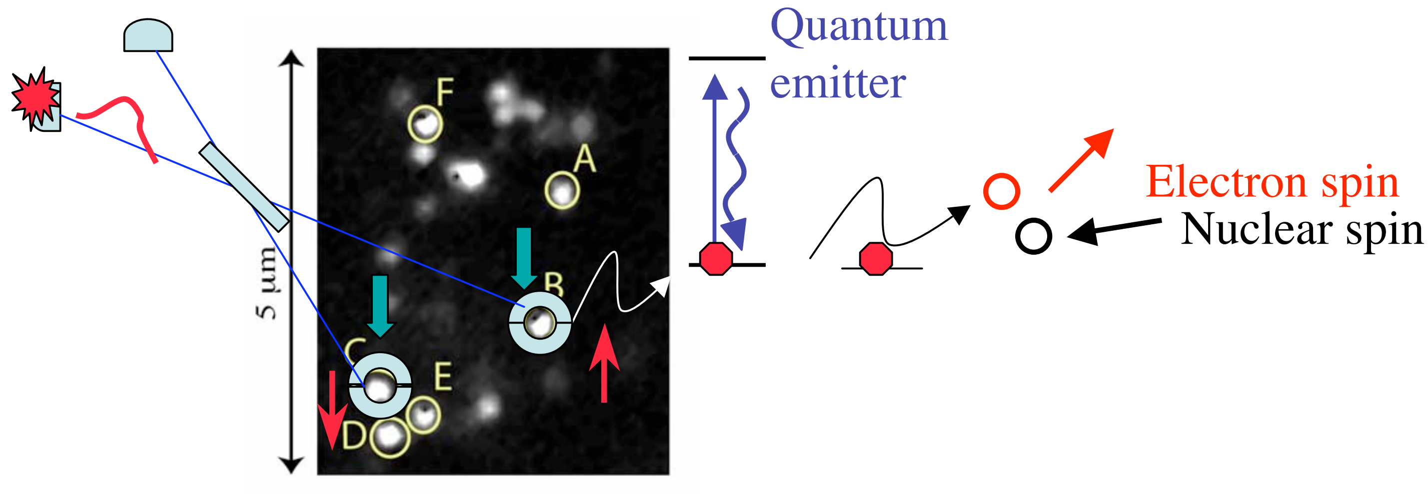
✓Challenge:

coupling between individual, remote, randomly located registers

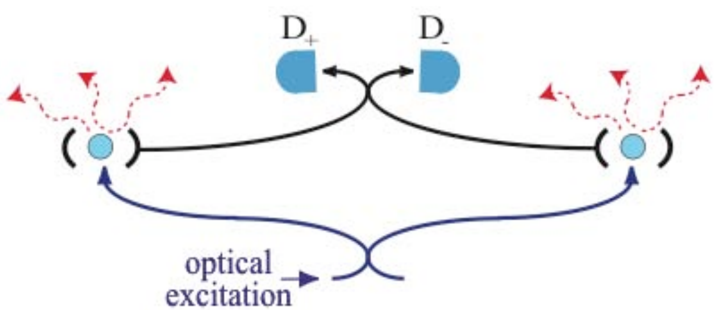


How to wire them up?

Linear optical connects for electron-nuclear registers



✓Electron spin entanglement via photon scattering & single photon interference

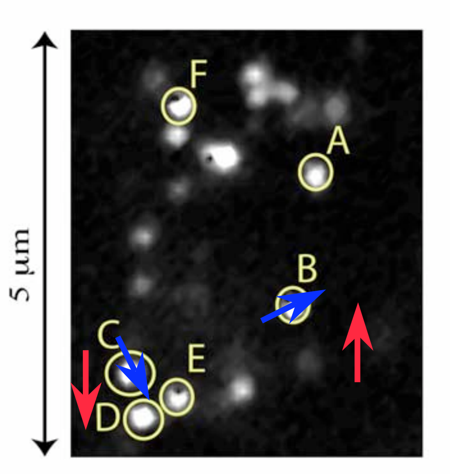


✓Two centers create interferometer: photon detection creates remote electronic singlets!

Example of probabilistic entanglement:

L.Duan, M.Lukin, I. Cirac, P.Zoller Nature 2001, atomic ensembles: experiments Caltech,Gatech,Stanford,Harvard
I.Cirac and P.Zoller (atoms), L.Duan, C.Monroe (ions), many others

Useful quantum processors from few coupled qubits



✓Idea: encode qubits in nuclear spins ("storage" qubits)

✓Entangle electrons ("communication" qubits) probabilistically without destroying nuclear qubits

✓Perform deterministic quantum gates between remote nuclei via electron-nuclear coupling: "teleportation based gates"

✓Operations between any pairs at random locations can be performed simultaneously: purely optical scaling possible

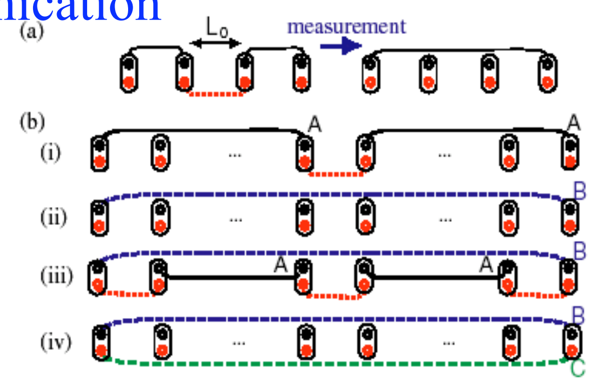
- quantum repeaters for long-distance communication

  L.Childress, J.Taylor, A.Sorensen. MDL, 2004

- fault tolerant quantum computation

  possibly with very high error thresholds

  L.Jiang, J.Taylor et al, (quant-ph0703029)



✓ Small registers can be efficiently scaled!

Progress: efficient entanglement requires narrow optical lines and efficient photon collection

✓Progress: narrow, stable, tunable optical lines in NV centers

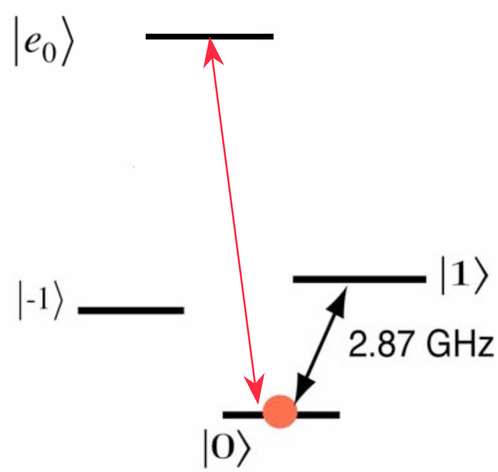
Resonant excitation

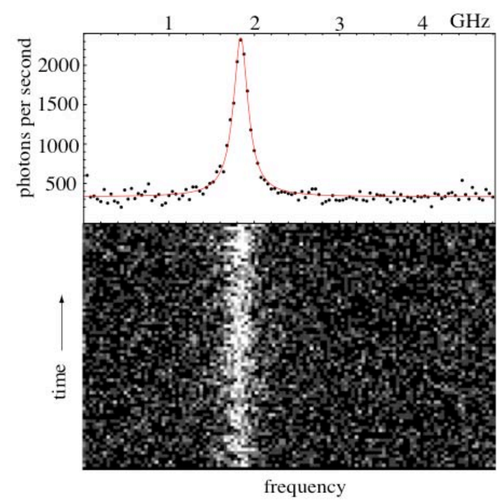
@ 637 nm, T~10 K

Jelezko et al (Stuttgart),

Santori et al (HP)

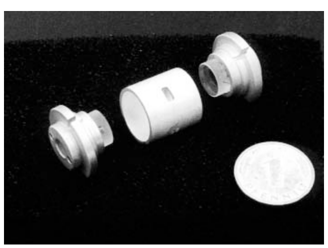
Dutt et al (Harvard)

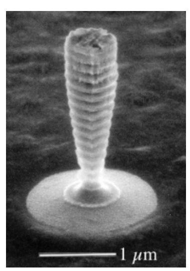


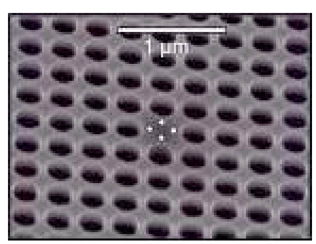


✓Approaches to efficient photon collection

Cavity QED: from Fabri-Perot to photonic crystals



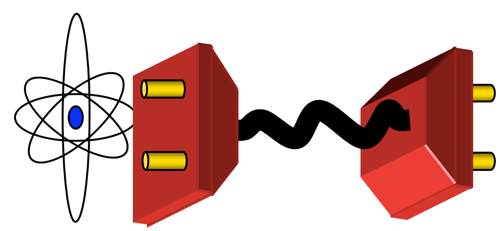




Kimble, Rempe, Yamamoto, Vuckovic, Imamoglu, Loncar …

New approach:

nanowire surface plasmons



Chang et al, PRL (2006) theory

Akimov et al, (2007) experiment

Outlook

New systems: e.g. other nano-tubes, other carbon-based materials

New applications:
e.g. ultra-sensitive, high resolution magnetometer
based on NV electron spins

New interface of NMR, mesoscopics, quantum optics, photonics, materials technology and quantum information

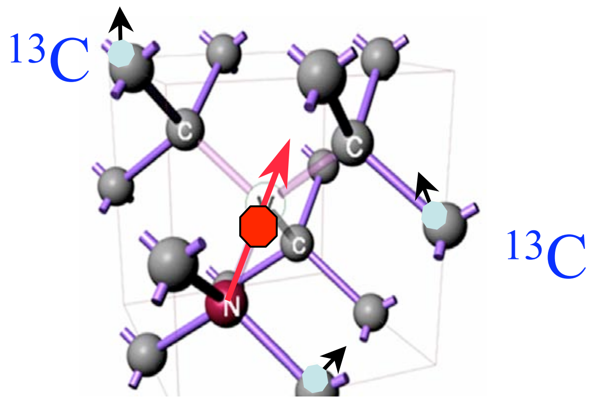
NMR manipulation of multi-qubit register with high polarization and single spins addressing

Entanglement of remote nuclear
spins in solid-state

Systems for efficient photon collection: photonic crystals, plasmons…

Quantum repeaters and novel approaches to FTQC,
e.g. measurement-based, cluster-state…

Summary

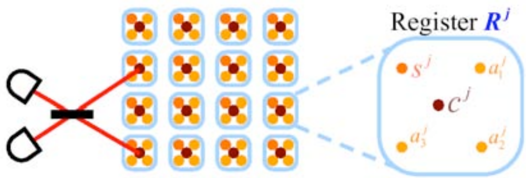


✓Understanding (nuclear spin) environment of single electrons

- Addressing individual nuclear spins in diamond lattice
- Coherent coupling between nuclear spin qubits

✓Hybrid approaches to scalable QI systems

- Measurement-based optical scaling of electron-nuclear spins registers
- New approaches to scalable system architecture



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$$$ NSF, Packard Foundations
quantum registers: ARO-MURI, NSF-PIF
plasmon QED: NSF-NIRT,DARPA