Qubits from Nitrogen-Vacancy Defects in Diamond

Based on: *Coherent Dynamics of Coupled Electron and Nuclear Spins in Diamond*. L. Childress, M.V. Gurudev Dutt, J.M. Taylor, A.S. Zibrov, F. Jelezko, J. Warchtrup, P.R. Hemmer and M.D. Lukin. Science 314, 281 (2006)

David McKay

Group Meeting, June 10, 2009

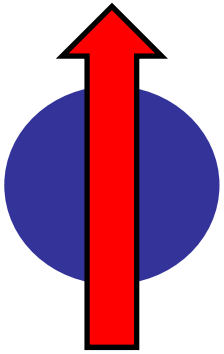
Outline

- What is a nitrogen vacancy
- Explaining the spectroscopy (and the notation!)
- What actually happens…

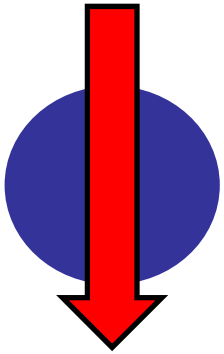
Electron Qubit

Qubit: Two state system we can put into a coherent superposition

What about the spin of an electron?



$|0\rangle$

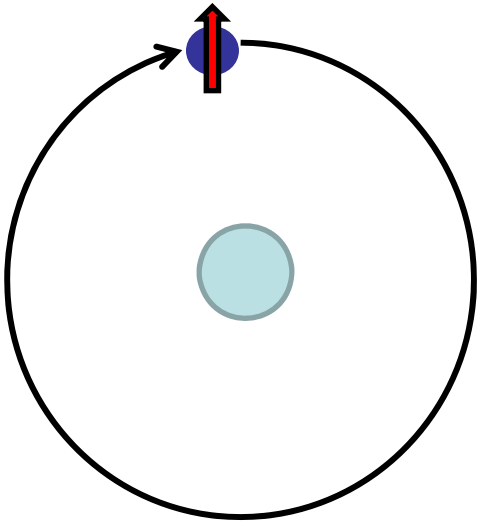


$|1\rangle$

How do we keep in it one place and initialize it?

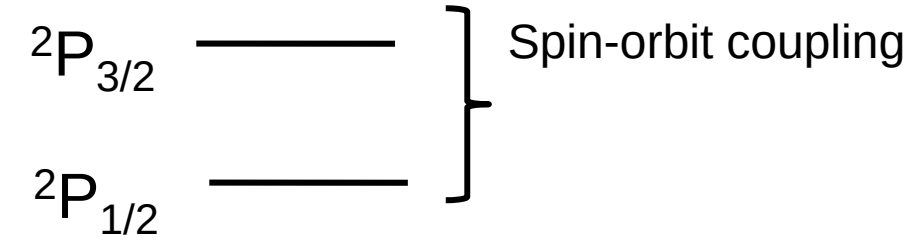
Let's Attach it to a Proton!

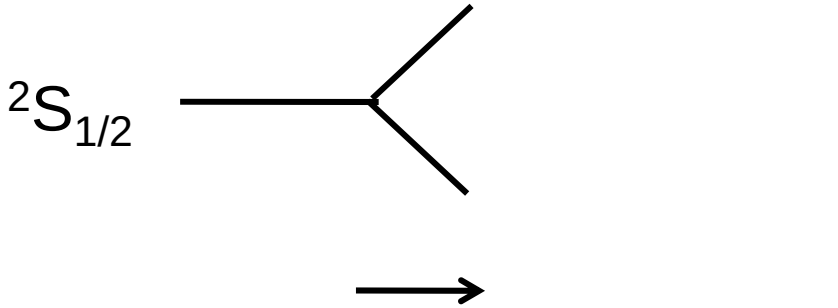
We could use the outer electron of an atom



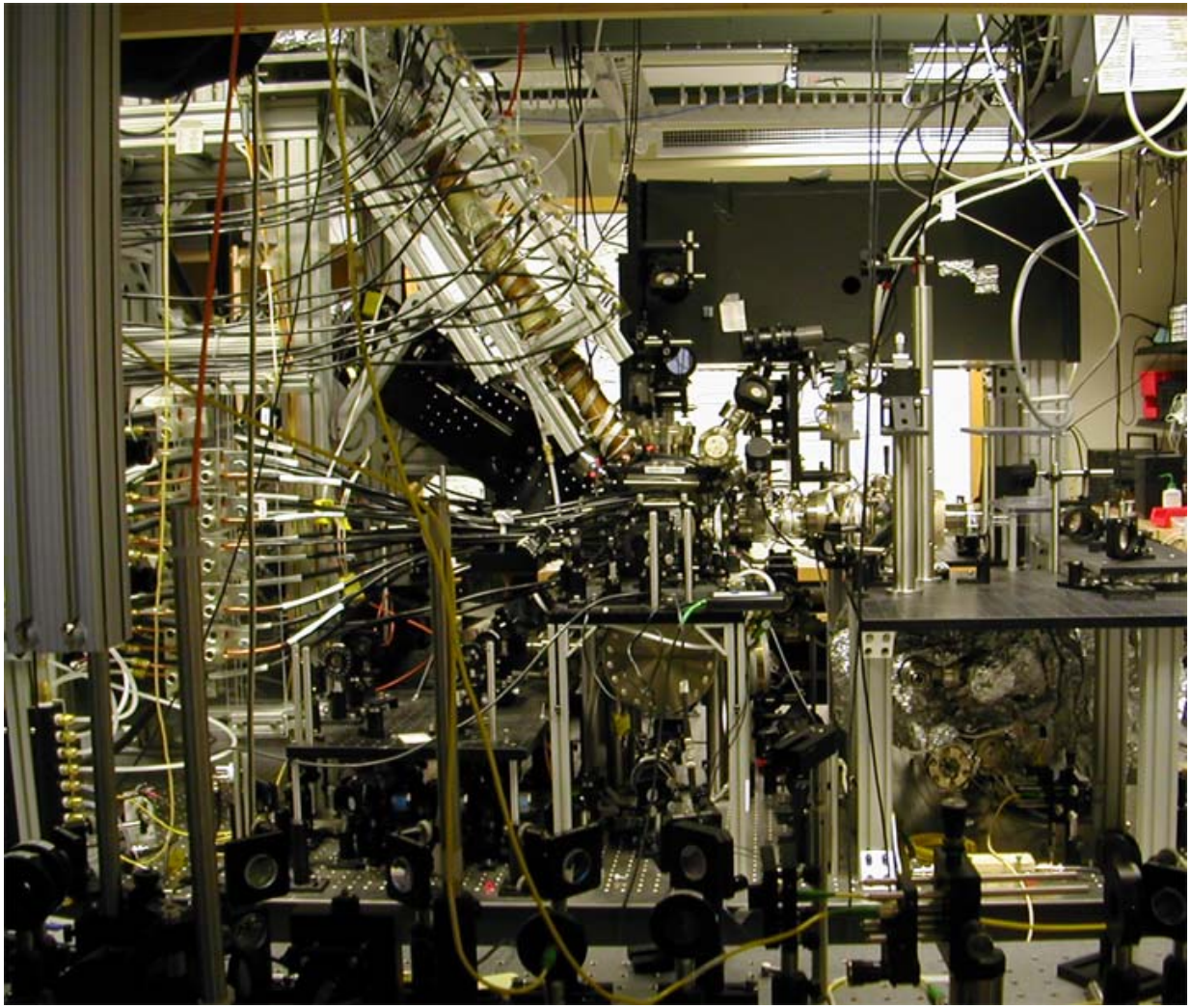
Get discrete states

$^{2S+1}L_{J=L+S}$





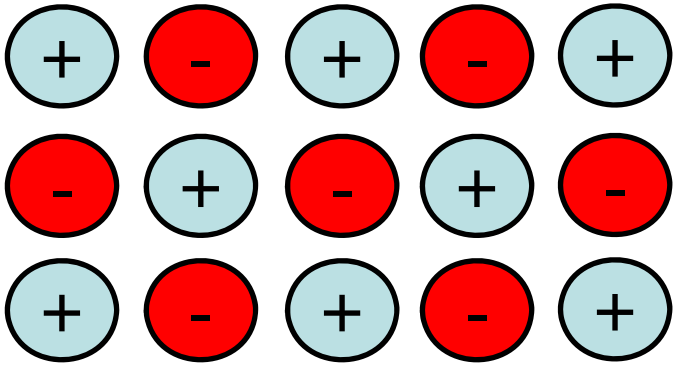
The catch



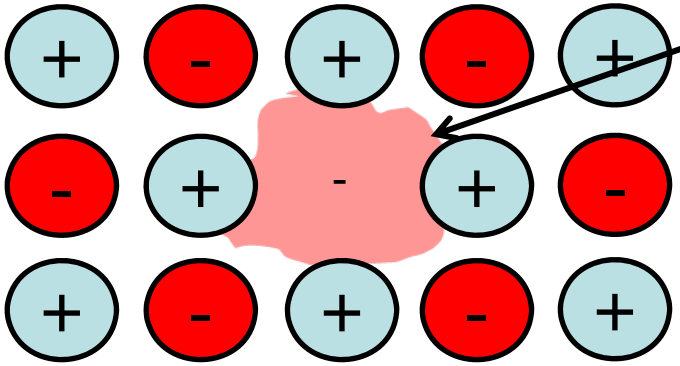
Atoms can be tricky to keep “still”

- Laser cooling
- Vacuum Systems
- Optical Lattices
- Not so ideal for mass production

What about Solid State?



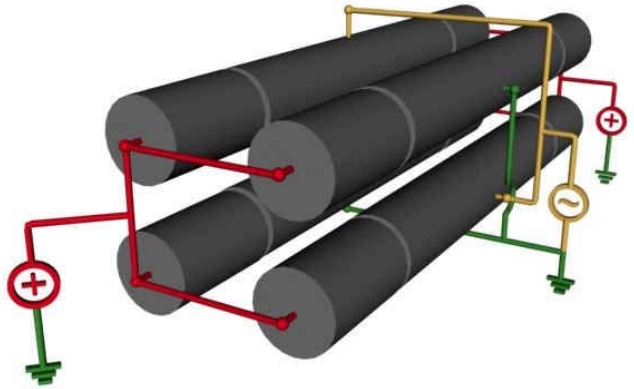
Add a defect



Consider an ionic crystal

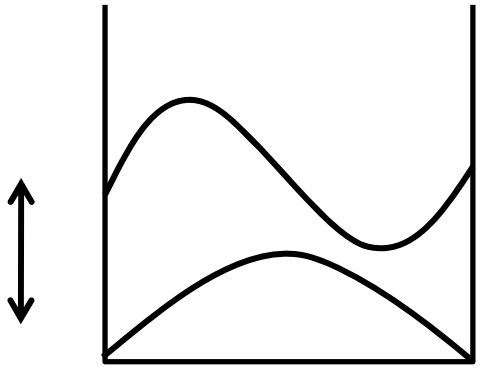
Electrons have a bandstructure. Optical excitation in the UV range.

Electron gets “trapped”



Electron in a Box

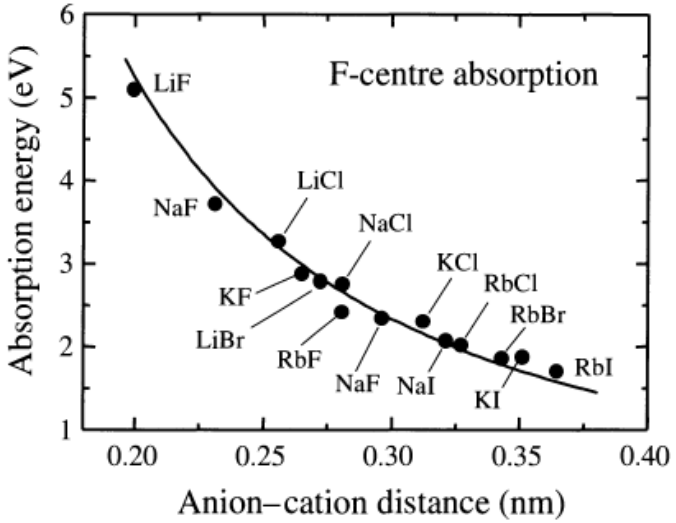
System can be modeled well by an electron in a box



a

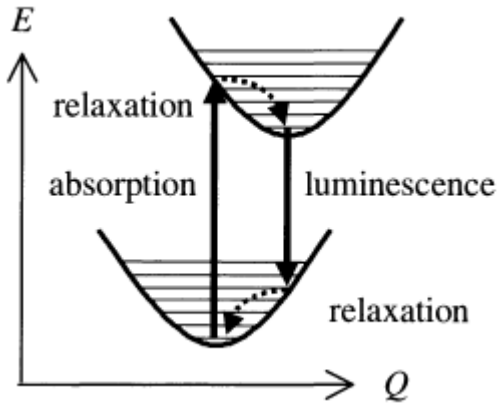
$E=(hk)^2/2m$

$\propto 1/a^2$



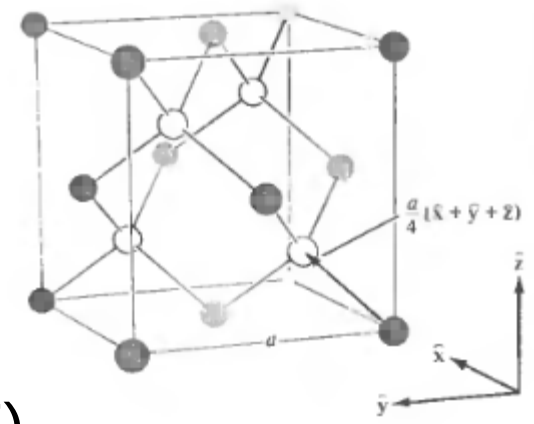
Energy separation is in the visible – “Colour Centres”

One complication is coupling to lattice phonons. This can be modeled as the ground and excited states being harmonic oscillators. The transition between 0^{th} harmonic oscillator modes is called the **zero phonon line**



Vacancies in Diamond

Diamond – Lattice of Carbon atoms with 5.5eV (225nm) band gap



Nitrogen-Vacancy (NV^-)
A type of colour center (discovered 1977)

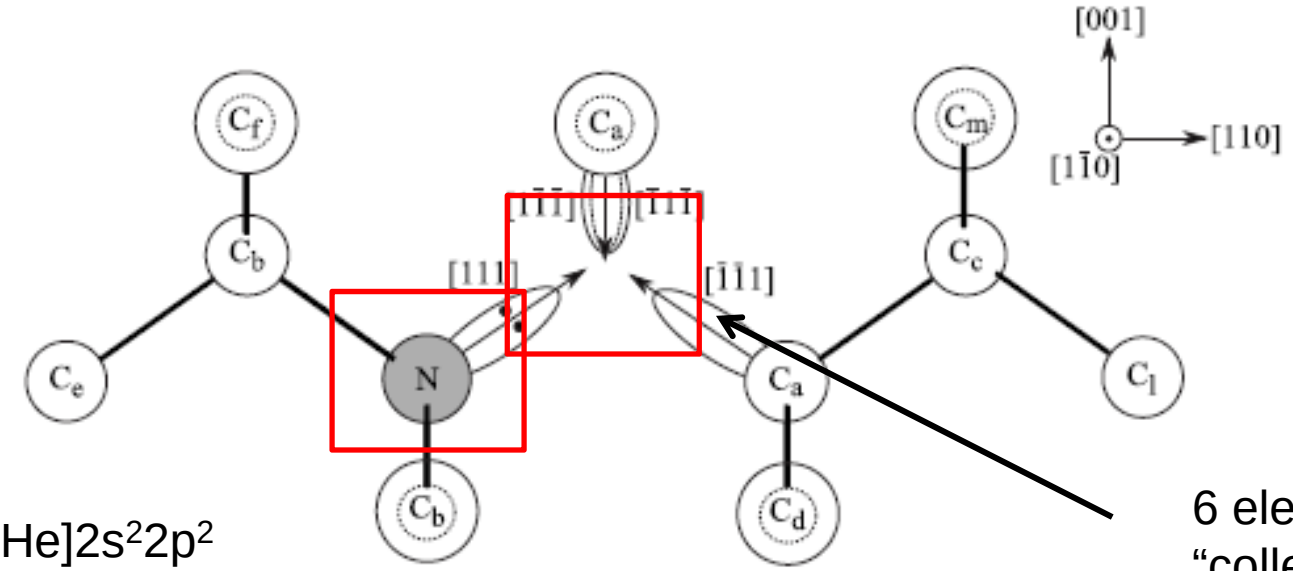
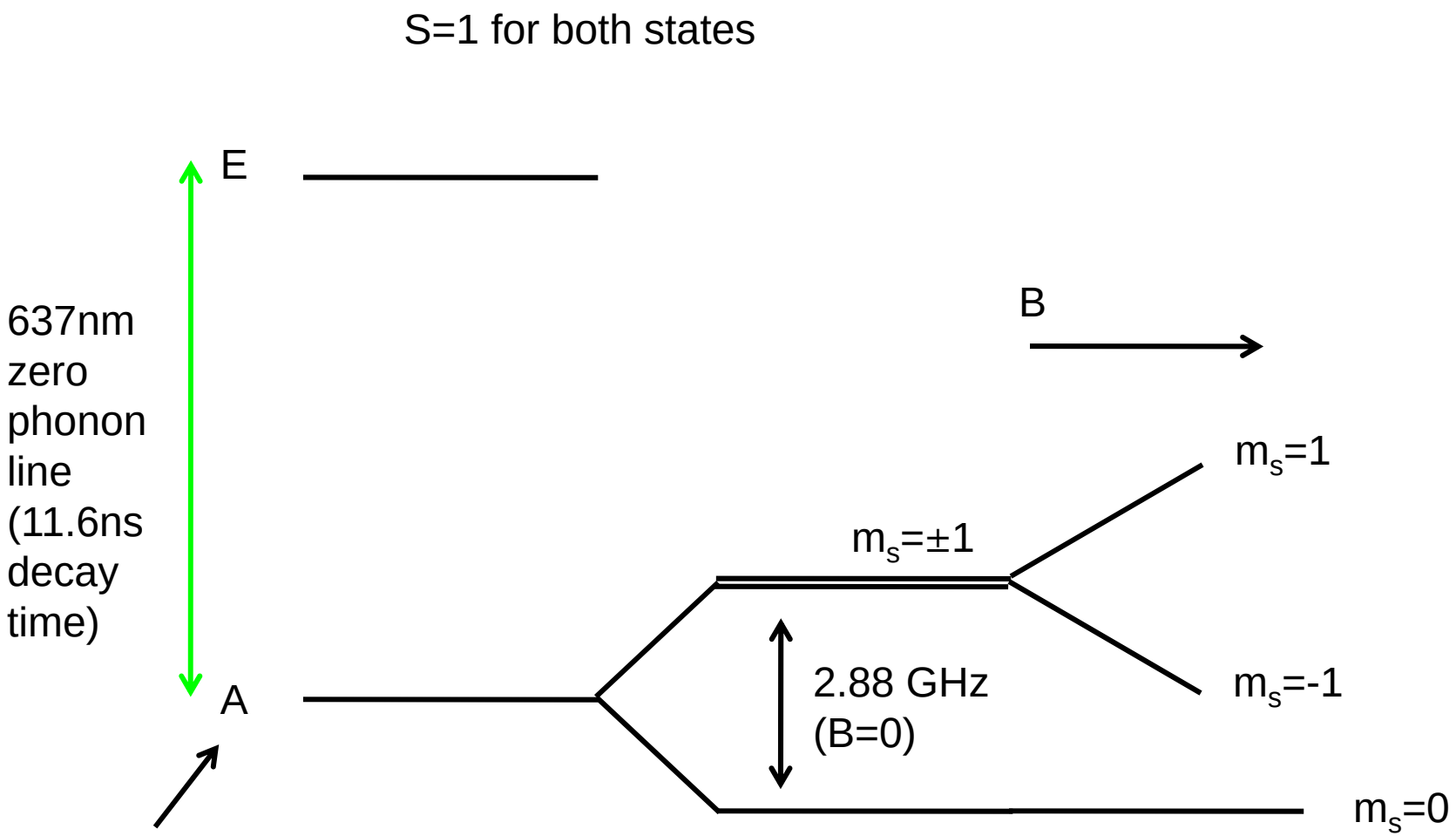


Image from PRB 79, 075203 (2009)

C: [He]$2s^2 2p^2$
N: [He]$2s^2 2p^3$

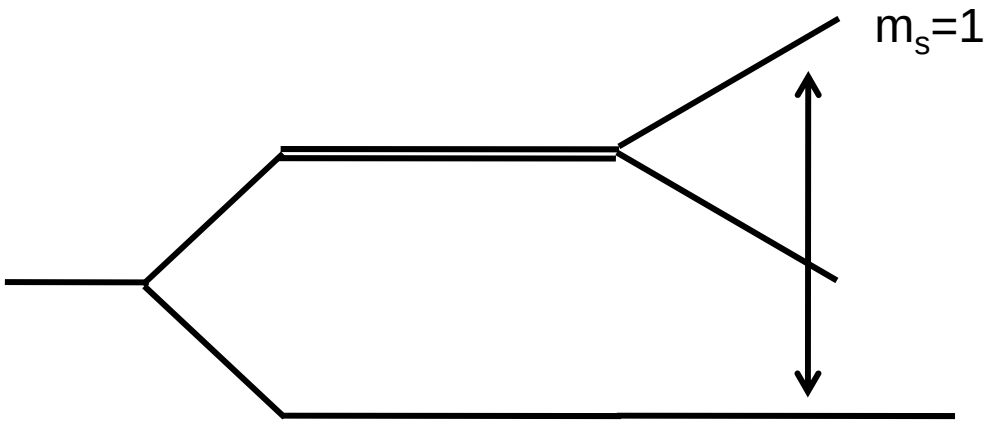
6 electrons "collect" into the vacancy

Explaining the Spectroscopy



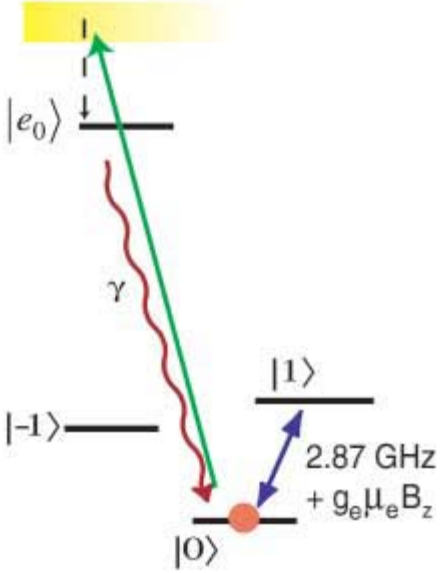
What are these? Equivalent of S,P,D,… for the symmetry of the NV center (not spherical! Trigonal symmetry)

The Experiment

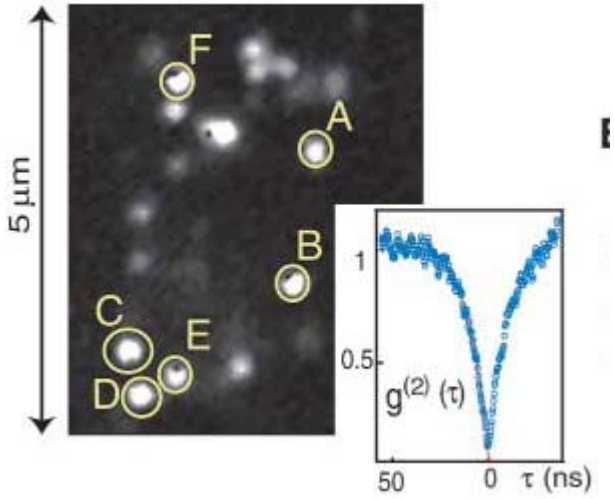


Investigate the properties of this two state system.

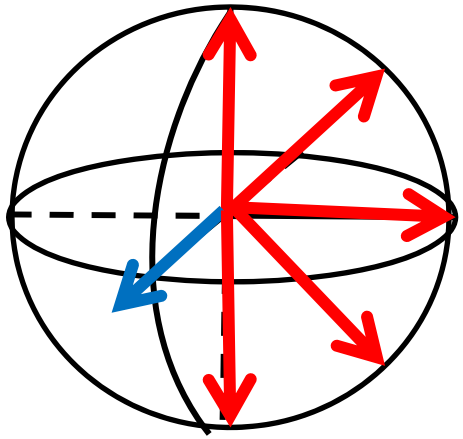
Detection Scheme ($|0\rangle$ has stronger coupling to $|e\rangle$)

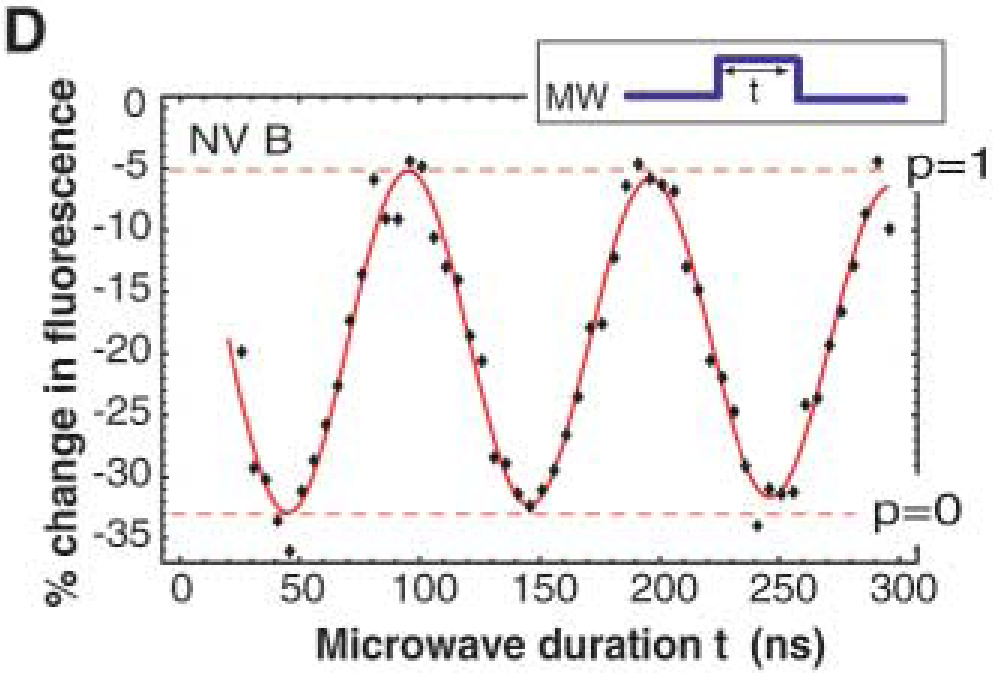


Find the NV centers

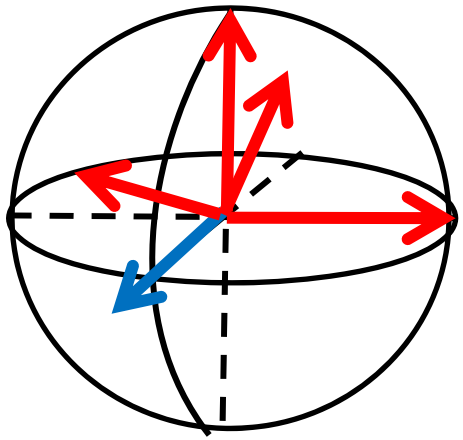


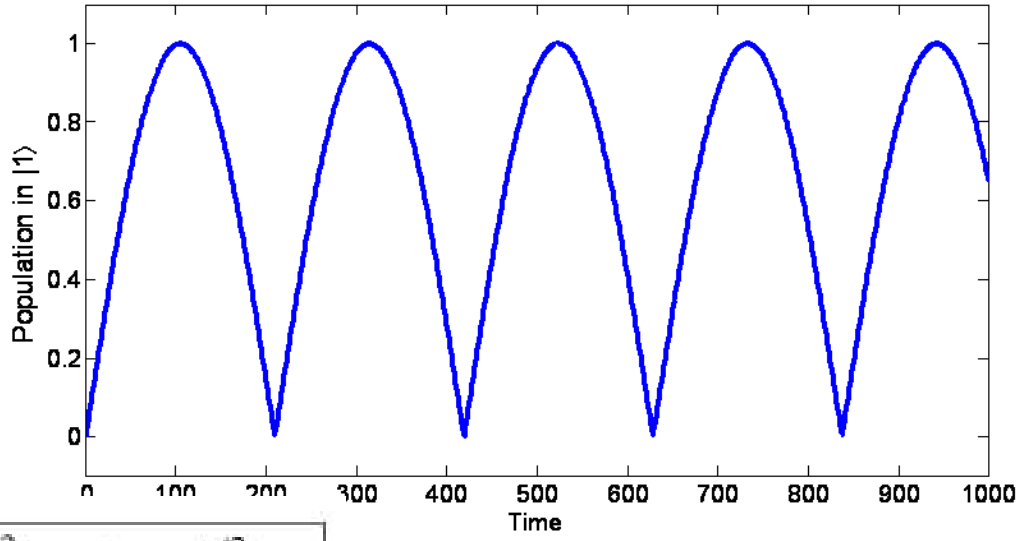
Rabi Oscillations

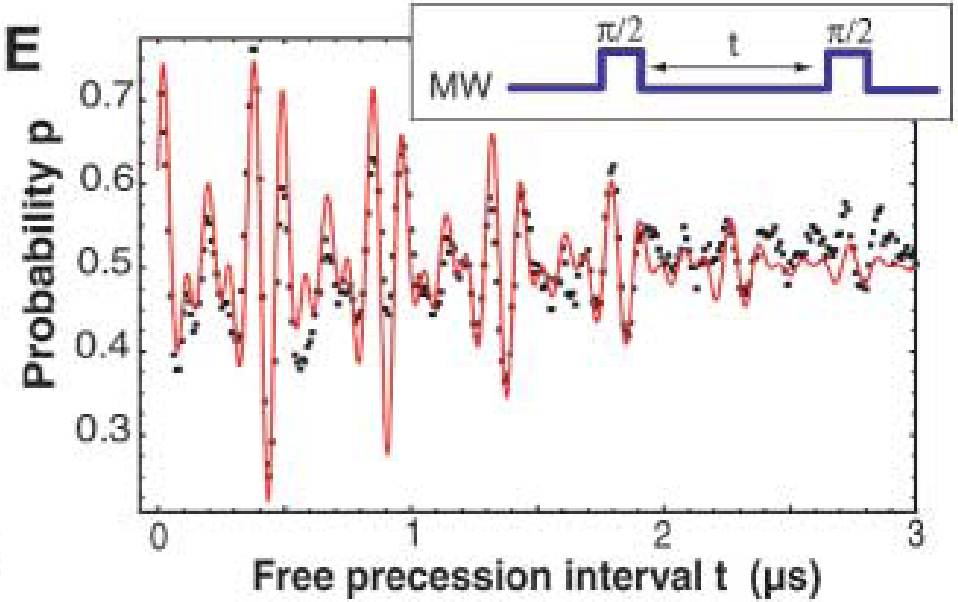




Ramsey Fringes

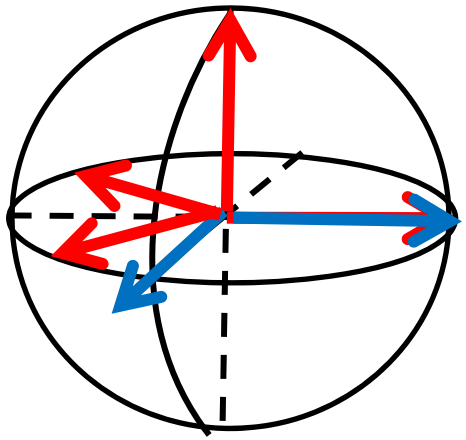




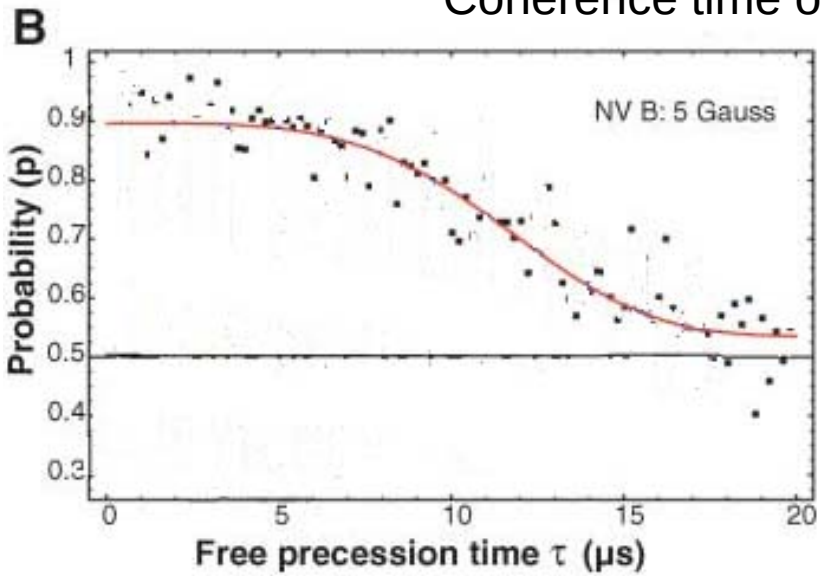


1.7(2) us dephasing time

Spin Echo (Spin Echo)

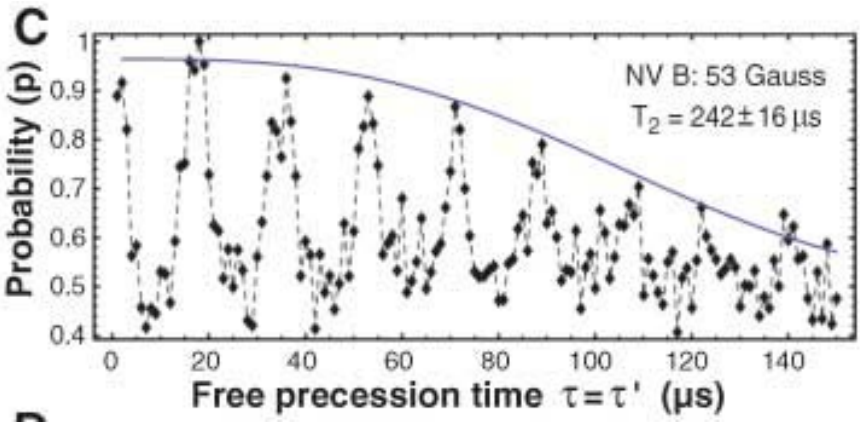


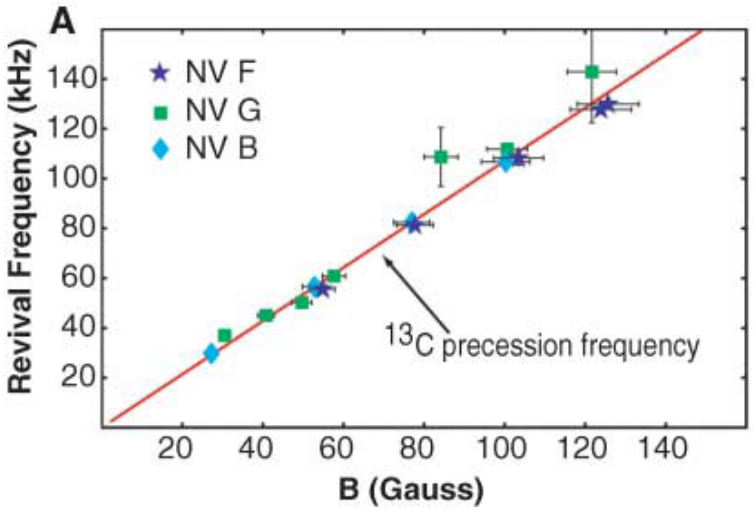
Coherence time of 13us



But as they turn a magnetic field up

(Note: Black dots are the same as the red curve above)





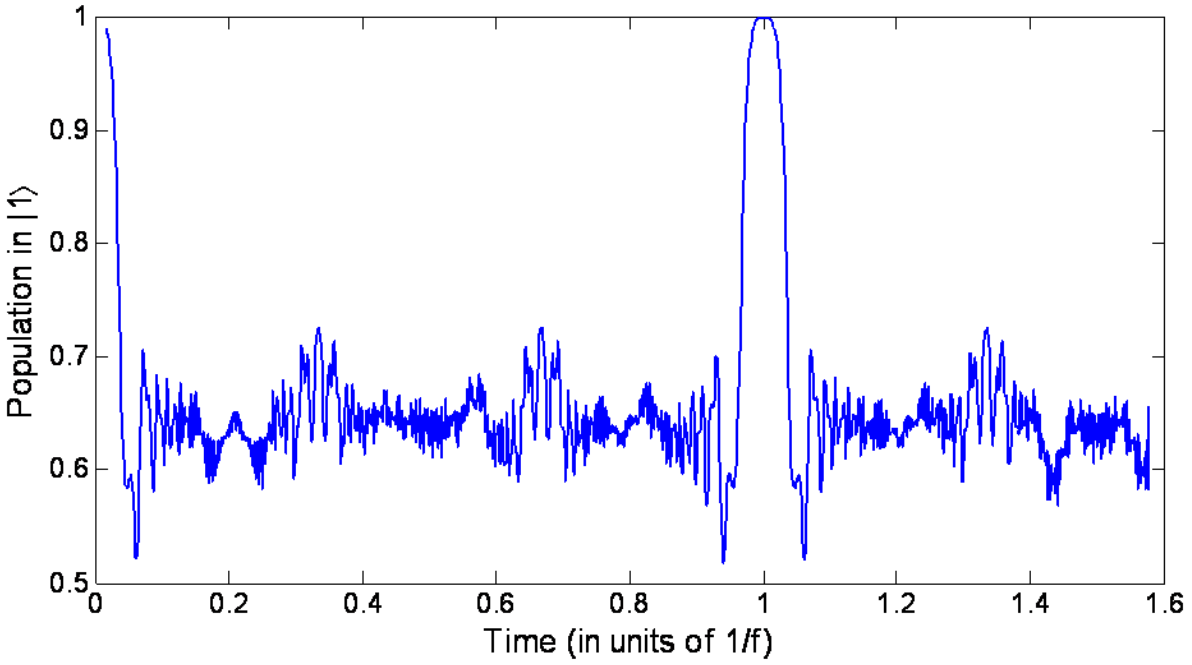
Understanding the Result

Assume the local B-field is the applied field plus an oscillating field

$$H = \mu_B S_z (B_0 + B_1 \sin \omega t)$$

$$\Psi = \begin{bmatrix} e^{i\mu_B (B_0 t + \frac{B_1}{\omega} \cos \omega t)} & 0 \\ 0 & 1 \end{bmatrix}$$

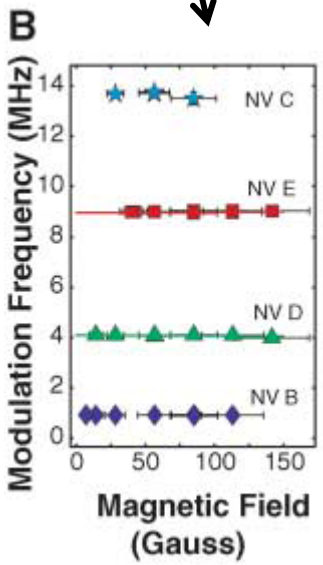
Simulation of the Spin Echo (with averaging)

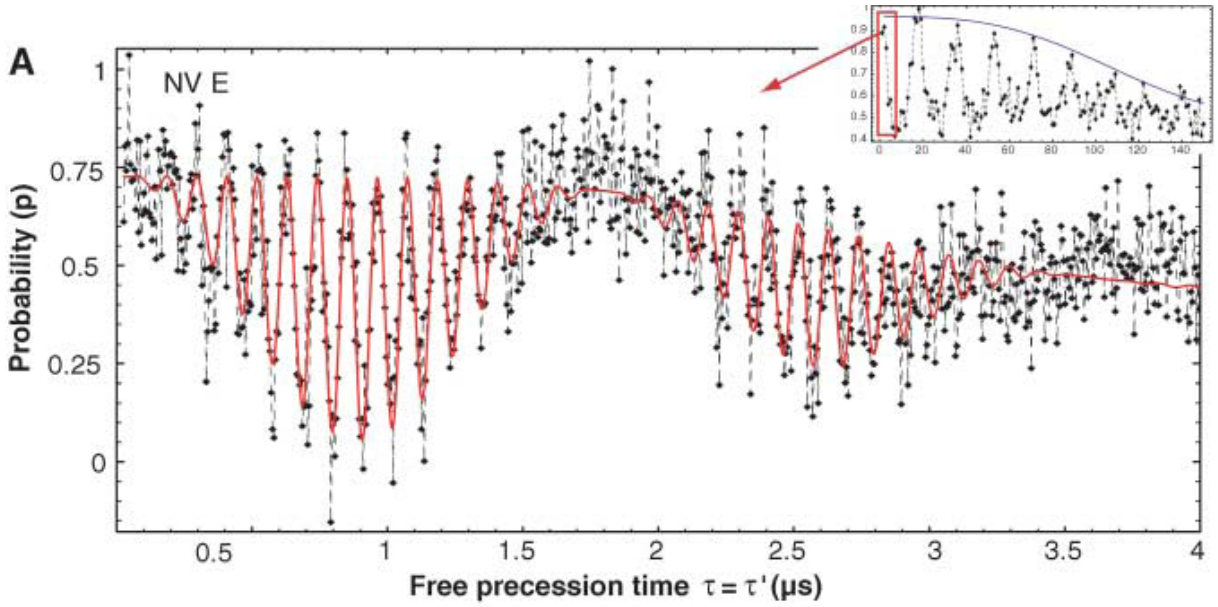


What about at short times

Fast modulation

Dependent on which NV center was analyzed





Hyperfine coupling to local spins! Possible mechanism for addressing local nuclear spins.

Conclusions/Future Results

- NV centers can be used as a two-state system.
- Main interactions are with C-13 nuclear spins
- Since this paper
  - Transfer of coherent information to these spins (Science 316, 1312 [2007])
  - Entanglement with these spins (Science 320, 1326 [2008])
  - Using NV centers for magnetometry (Nature 455, 644[2008] and 648[2008]