Optical emitters for quantum technologies

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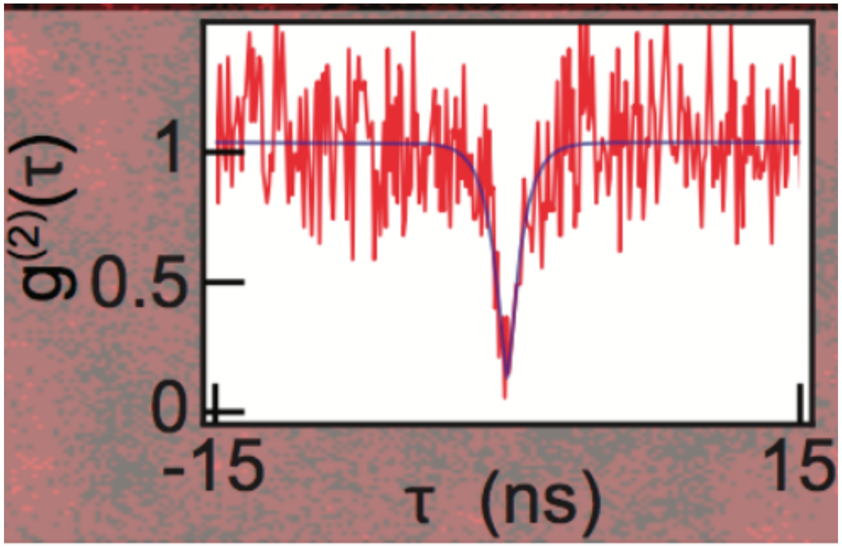
Outline

- Desiderata for quantum applications
- Survey of quantum emitter systems
- Optical coherence and interactions with the environment
- Spin coherence and interactions with the environment

Desiderata for quantum applications

Single photon sources: for QKD, LOQC

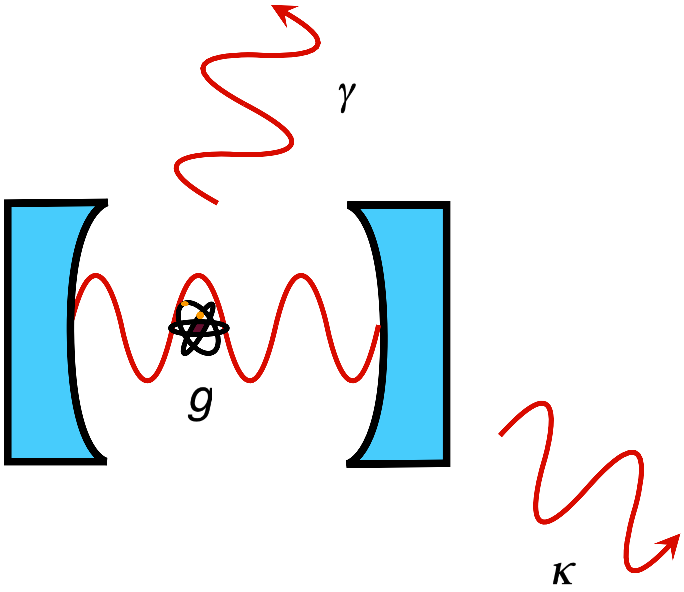
- Brightness: short excited state lifetime, high quantum efficiency
- Purity: low background, high collection efficiency
- Coherence: transform-limited photons



Desiderata for quantum applications

Using quantum systems to control light: cavity QED for single photon switches, transistors

- Can parametrize with g, κ, γ
- Need “good” optical transition to realize full enhancement



cooperativity $\frac{g^2}{\kappa\gamma} \propto \frac{3}{4\pi^2}\frac{\lambda^3}{n^3}\frac{Q}{V}$

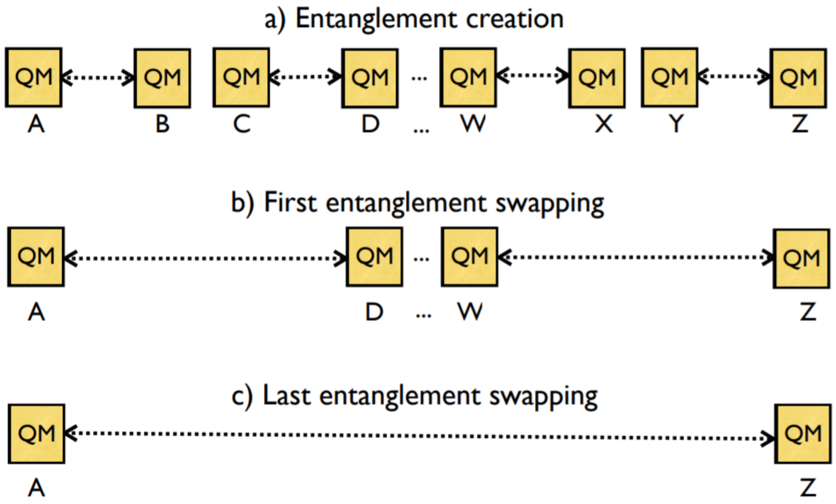
single photon Rabi frequency $g \propto E_0 \equiv \sqrt{\frac{\hbar\omega}{\varepsilon_0 V}}$

cavity decay rate $\kappa = \frac{\omega}{Q}$

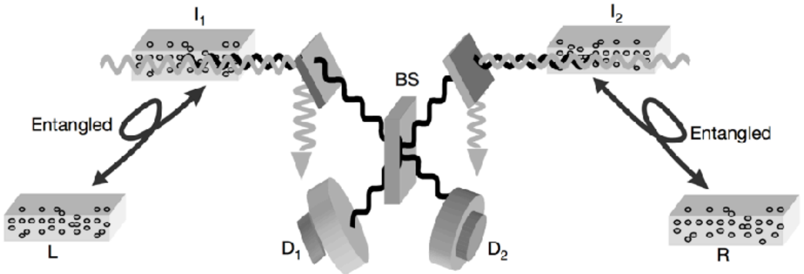
Desiderata for quantum applications

Quantum networks: QKD, modular quantum computing, distributed sensing, tests of fundamental physics

Distribute entanglement among remote quantum memories



Sangouard *et al.*,*Rev. Mod. Phys*. **83**, 33 (2011)

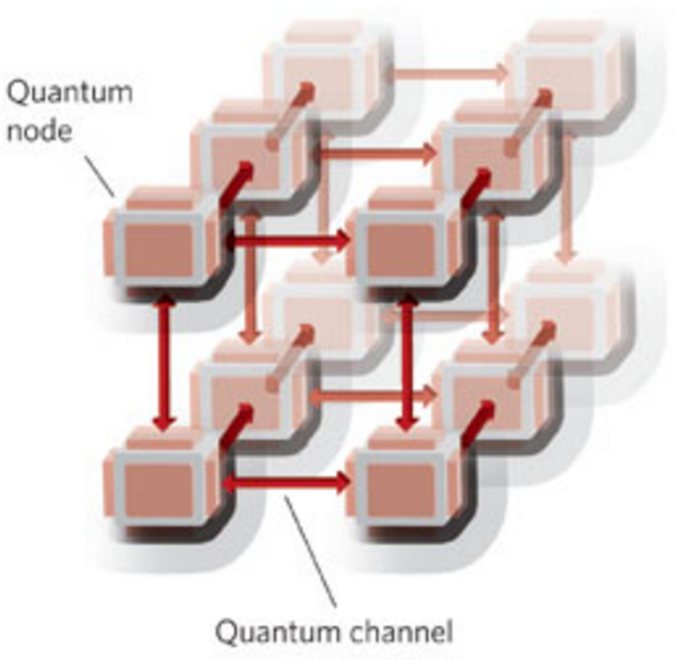


Duan, Lukin, Cirac, Zoller, Nature 2001

Desiderata for quantum applications

Quantum networks

- Bright source of identical single photons with high optical coherence
- Entangled with a quantum memory
- Long spin coherence

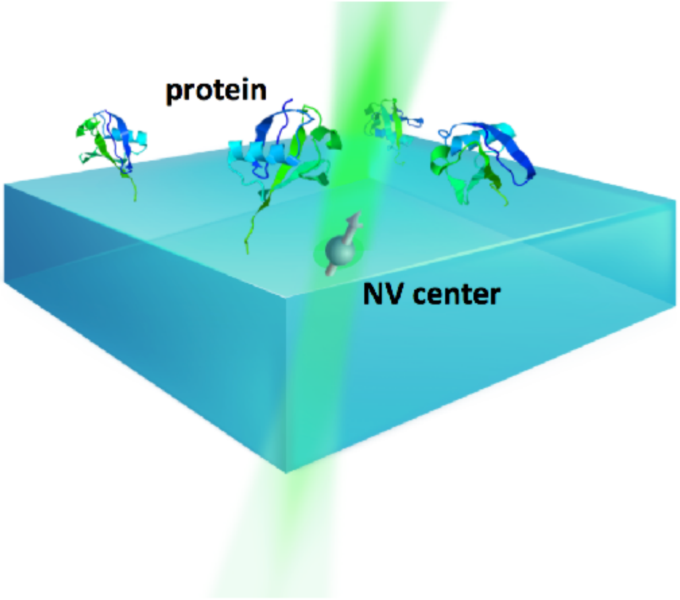


Kimble, Nature 2008

Desiderata for quantum applications

Quantum sensors

- Long spin coherence at room temperature
- Optical readout of spin



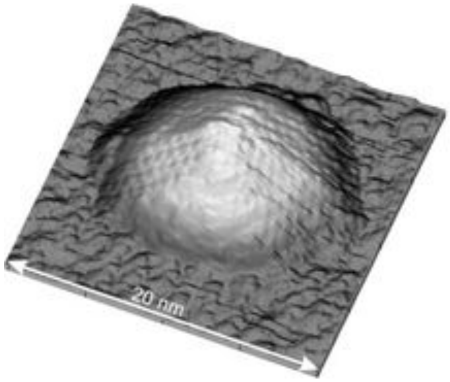
Lovchinsky *Science* 2016

Survey of quantum systems

Extent of wavefunction

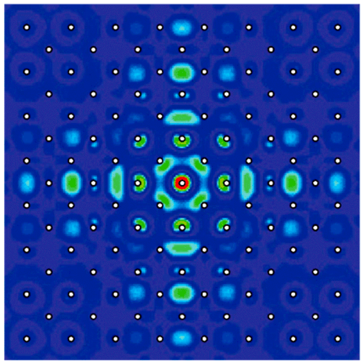
More lattice-like **More atom-like**

10-100 nm **nm** **Å**



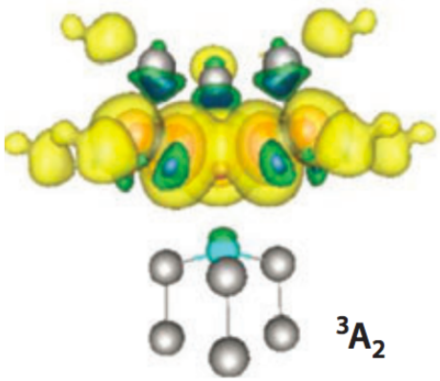
Eisele et al, J. Appl Phys 2008

Quantum dots



Das Sarma 2005

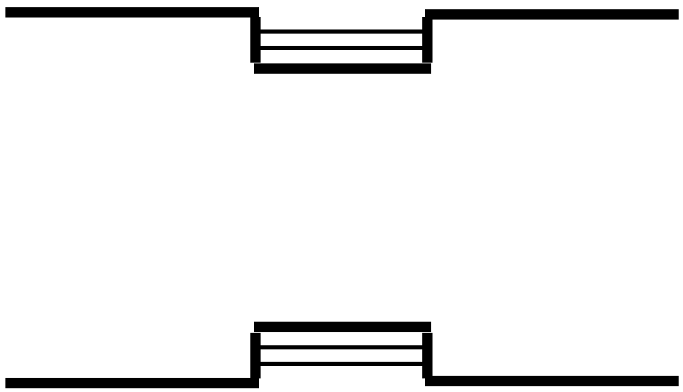
Shallow donors



Color centers

Quantum dots

- Strain quantum dots (InAs in GaAs) from heteroepitaxial growth, assemble spontaneously during MBE



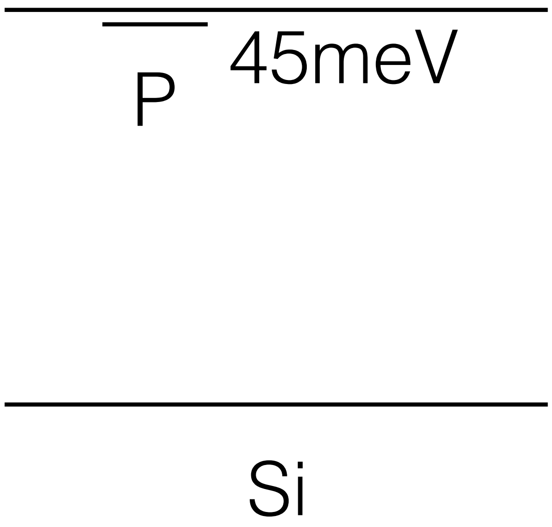
- High quantum efficiency, transform-limited optical linewidth: τ~100ps

- Electron spin coherence $T_2 < 100$ns

- broad inhomogeneous distribution of optical transition 10-100nm

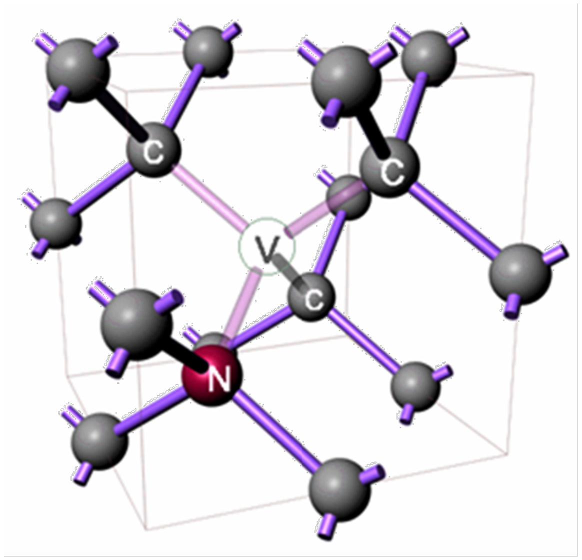
Shallow donors

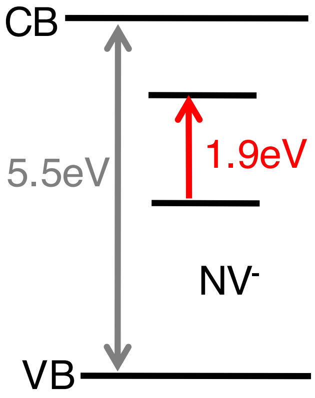
- Electron bound to P+ at low temperature, hydrogenic orbitals
- T_1 ~ 100s, T_2 ~ 1s at 4K for isotopically purified Si
- optical transitions mostly ionizing



Color centers

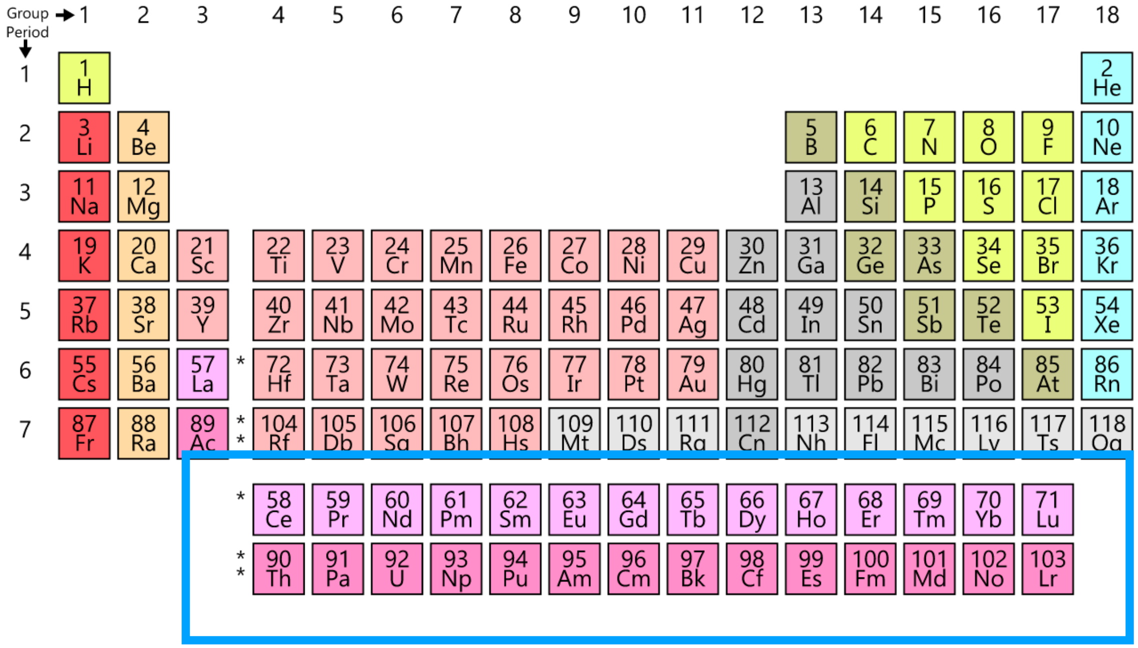
- T_1 ~ 10ms at room temperature, hours at cryogenic temperatures
- T_2 can be T_1 limited for isotopically purified diamond
- optical spin readout at room temperature
- narrow, coherent optical transitions at low temperature (but…)





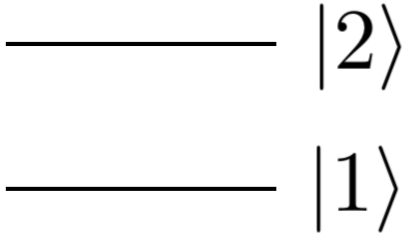
Rare earth ions

- buried f-shells, same optical transition frequency in every host material
- T_1 ~ ms, T_2 ~us in known materials below 1K
- high quantum efficiency, but excited state lifetime ~ 10-100 ms



Group → Period ↓	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	57 La *	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	89 Ac **	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Nh	114 Fl	115 Mc	116 Lv	117 Ts	118 Og
			*	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu	
			**	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr	

Optical coherence



parametrize atom-photon interaction:

Write down the susceptibility of a medium of perfect two-level atoms

optical transition dipole

$$\chi = i\frac{N}{V}\frac{\mu^2}{\hbar\epsilon_0}(\rho_{11}-\rho_{22})\frac{1}{\gamma_{12}-i\delta}$$

density of atoms

detuning

$$\gamma_{12} = \frac{\gamma_1+\gamma_2}{2}$$

average decay rate

$$\hat{\rho} = \rho_{11}\left|1\right\rangle\left\langle1\right| + \rho_{12}\left|1\right\rangle\left\langle2\right| + \rho_{21}\left|2\right\rangle\left\langle1\right| + \rho_{22}\left|2\right\rangle\left\langle2\right|$$

$$\chi = i\frac{N}{V}\frac{\mu^2}{\hbar\epsilon_0}(\rho_{11}-\rho_{22})\frac{1}{\gamma_{12}-i\delta}$$

can replace transition dipole with expression for Einstein A coefficient

$$\gamma = \frac{\mu^2}{3\pi\epsilon_0\hbar}\left(\frac{2\pi}{\lambda}\right)^3$$

$$\chi = i\frac{3}{8\pi^2}\frac{N}{V}\lambda^3(\rho_{11}-\rho_{22})\frac{\gamma}{\gamma_{12}-i\delta}$$

$$\chi = i\frac{3}{8\pi^2}\frac{N}{V}\lambda^3(\rho_{11} - \rho_{22})\frac{\gamma}{\gamma_{12} - i\delta}$$

on resonance, $\delta = 0$

in linear regime, $\rho_{11} = 1$
$\rho_{22} = 0$

$$\chi_0 = i\frac{3}{8\pi^2}\frac{N}{V}\lambda^3\frac{\gamma}{\gamma_{12}}$$

this is purely imaginary -> absorption, no refraction

The electric field through the medium will propagate as:

$$\mathcal{E}(x) = \mathcal{E}(0)e^{(-Im[\chi]+iRe[\chi])kx/2}$$

We also know Beer's Law

absorption cross section per atom

$$|\mathcal{E}|^2 = I(x) = I(0)e^{\frac{-N\sigma x}{2}}$$

Comparing expressions,

$$\sigma = \frac{3}{4\pi}\lambda^2\frac{\gamma}{\gamma_{12}}$$

$$\sigma = \frac{3}{4\pi}\lambda^2\frac{\gamma}{\gamma_{12}}$$

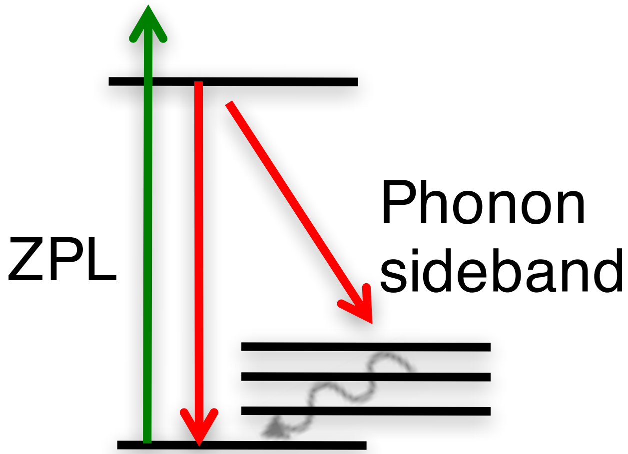
The absorption cross section can be λ^2! as long as

$$\gamma = \gamma_{12}$$

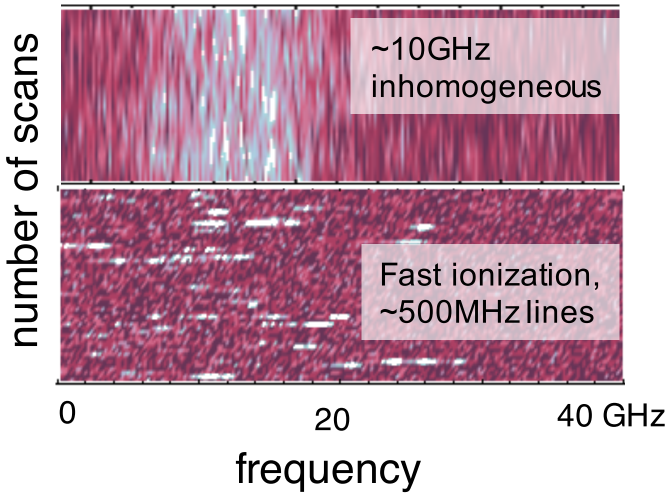
This condition is called *radiative broadening*, and will also correspond to a transform-limited linewidth

- no dephasing from non-radiative processes, no spectral diffusion, QE is unity

Interactions that degrade optical coherence



1. Emission of photon + phonon
2. Absorption of phonon, phonon mixing
3. Spectral diffusion



Spin coherence

Hamiltonian for spin in a magnetic field:

$$\hat{H} = -\frac{1}{2}\hbar\gamma\vec{\sigma}\cdot\vec{B}$$

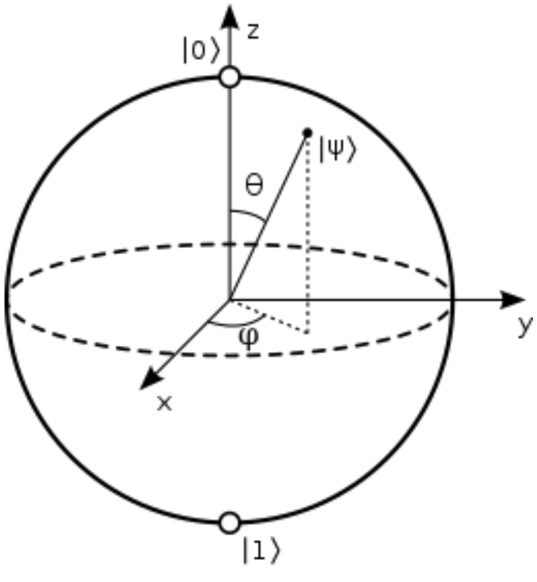
$$\gamma = \frac{g\mu_B}{\hbar}$$

Can write the evolution of a superposition: $|\psi(t=0)\rangle = \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)$ in an external magnetic field B_0 along the quantization axis

$$i\hbar \frac{\partial}{\partial t} |\psi(t)\rangle = \hat{H} |\psi(t)\rangle$$

$$|\psi(t)\rangle = \frac{1}{\sqrt{2}}(|0\rangle + e^{i\gamma B_0 t} |1\rangle)$$

Larmor precession around the Bloch sphere



In an AC magnetic field $B = B_1 cos\omega t\hat{x}$

solve in a rotating frame, rotating at Larmor frequency

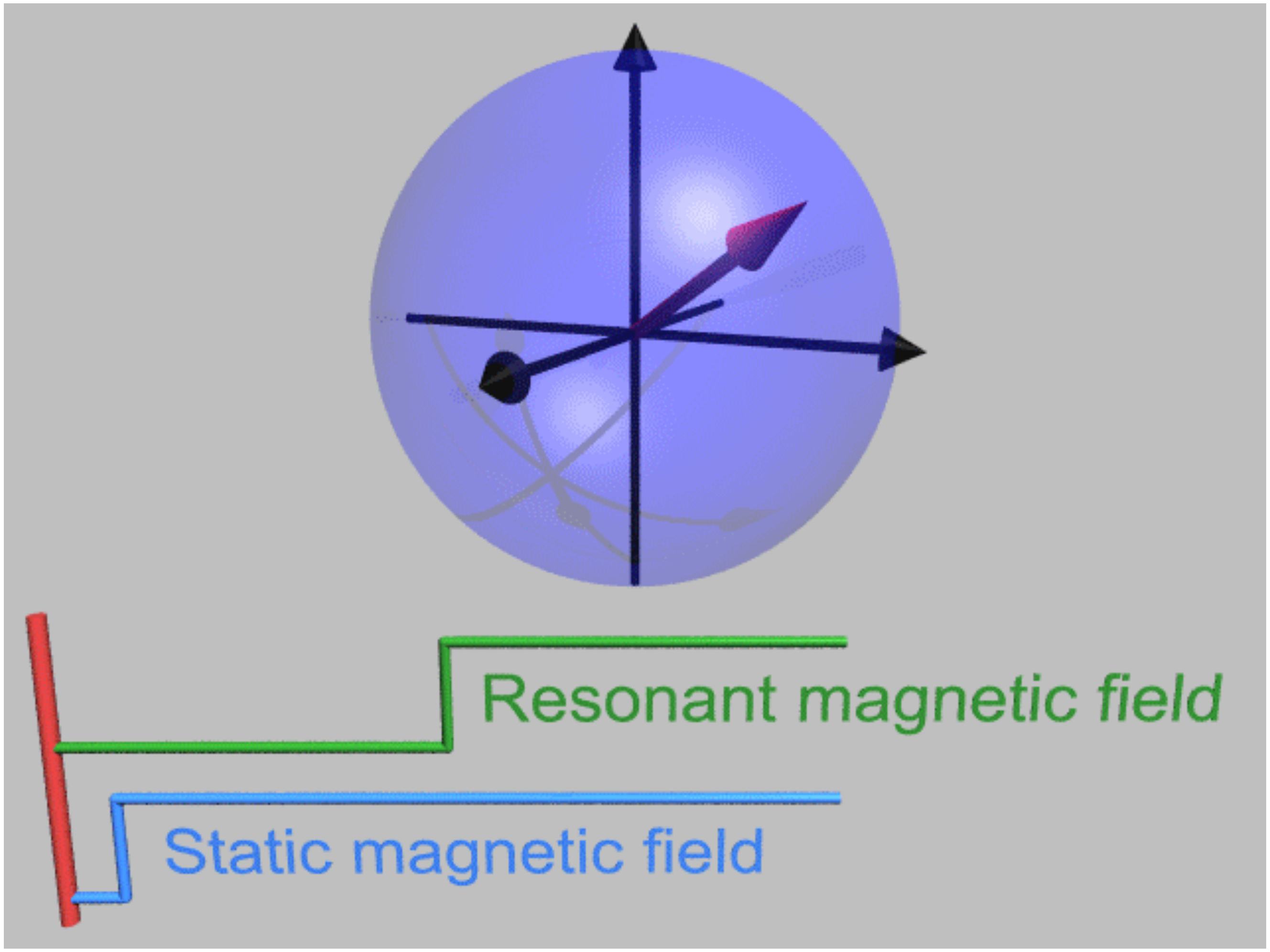
$$|\psi^*(t)\rangle = e^{i\omega_L\sigma_z t/2}\,|\psi(t)\rangle$$

apply rotating wave approximation, drive on resonance:

$$H'(t) = \hbar\Omega\sigma_x$$

$\Omega = \frac{\gamma B_1}{2}$ is the Rabi frequency

Magnetic resonance in the rotating frame

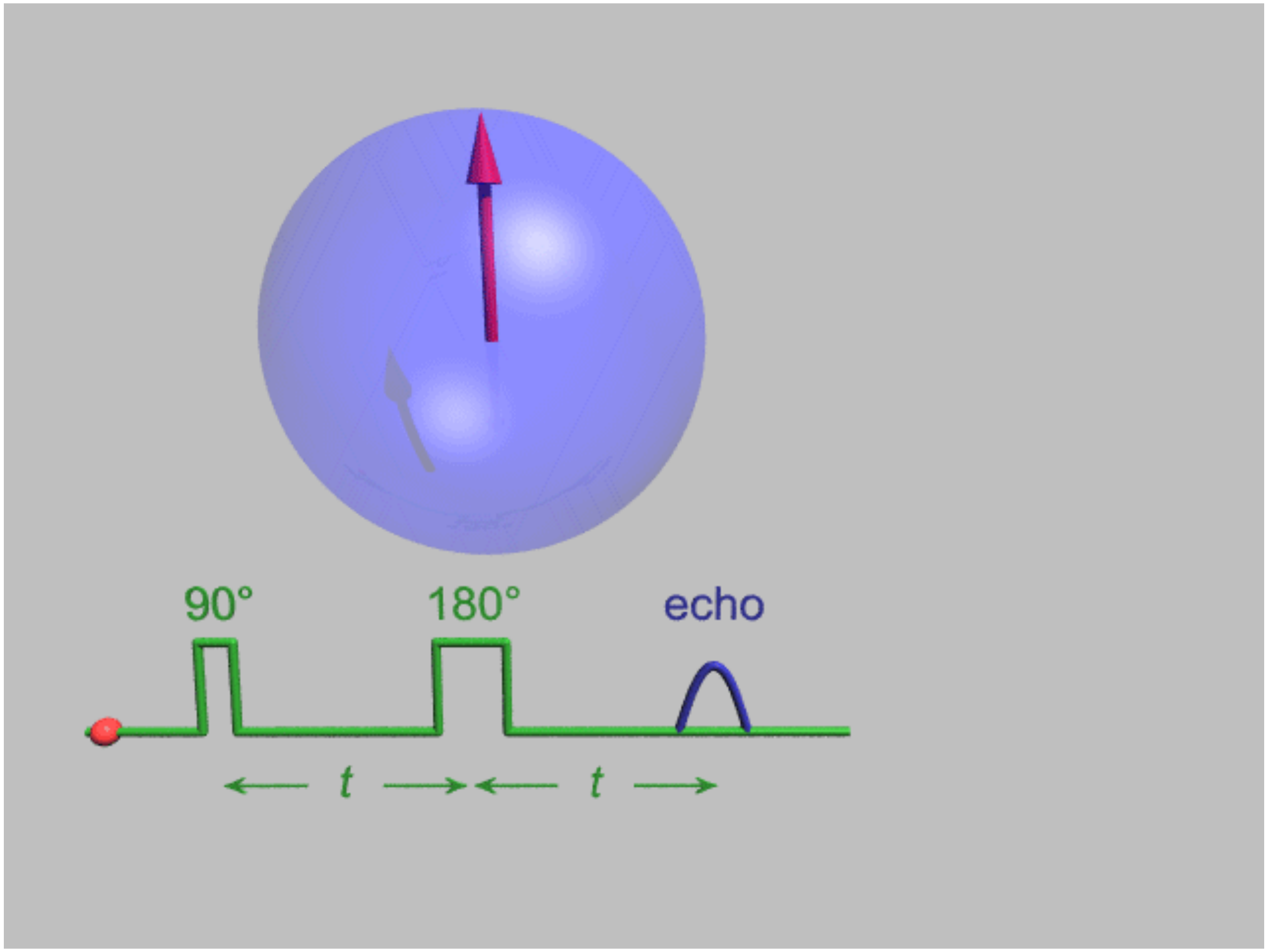


GW Morley

Dephasing T_2^*

- spins experience inhomogeneous magnetic field, will pick up different phase
  - static inhomogeneity -> ensemble linewidth broadening
  - slowly varying field -> spectral diffusion of magnetic resonance
- arise from hyperfine interactions, dipolar interactions with spins in the host

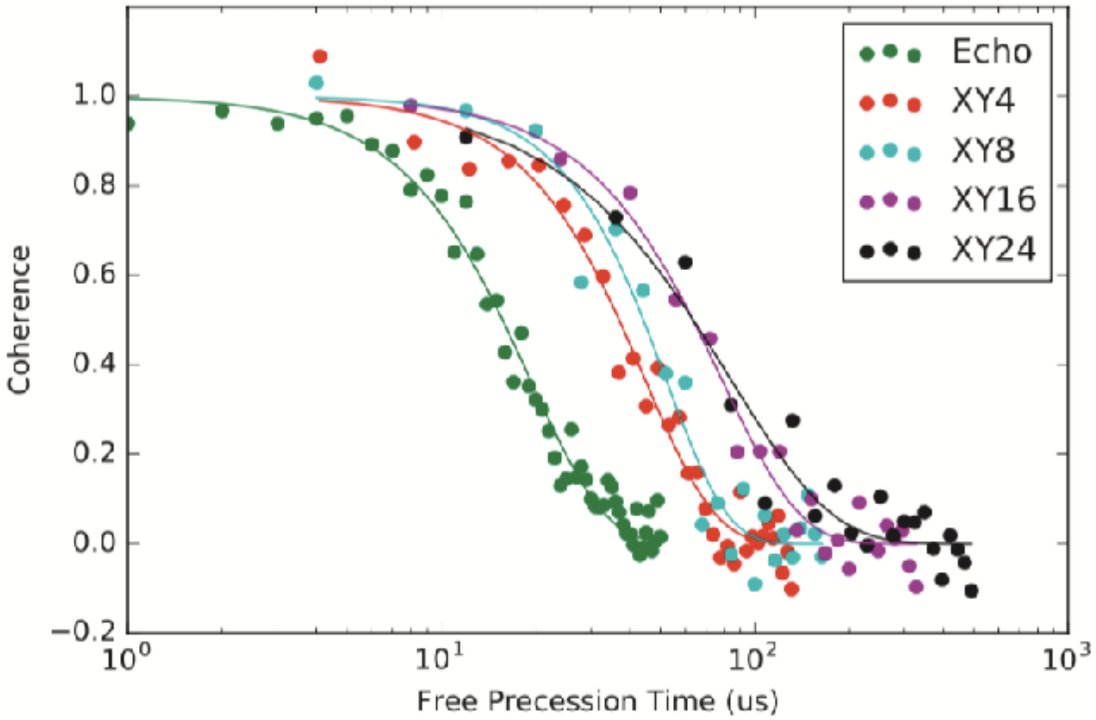
Hahn echo



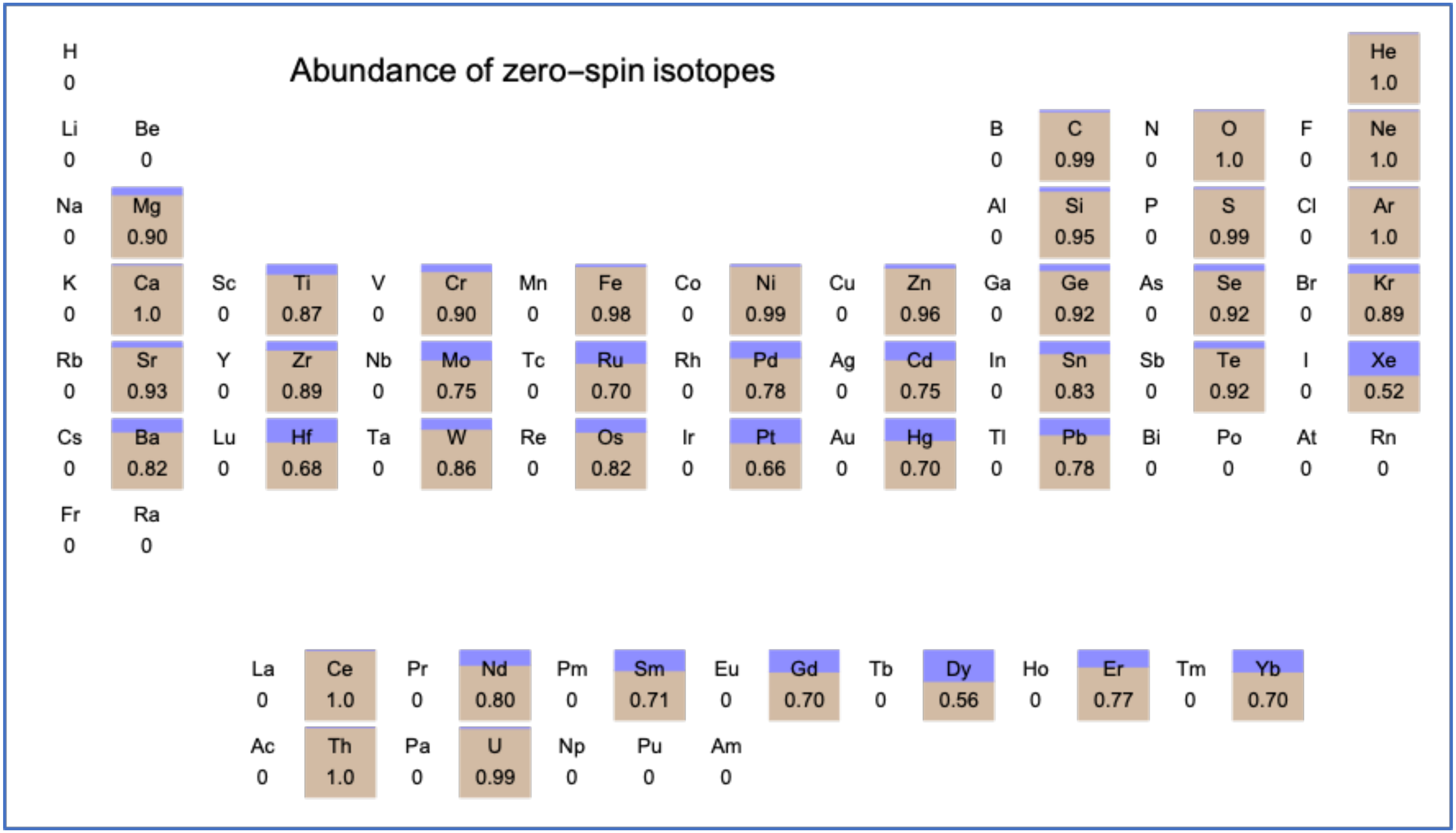
GW Morley

Decoherence T_2

- Remaining decoherence from higher frequency magnetic fields



conceptually, easy to achieve long T_2



Abundance of zero–spin isotopes

H 0																	He 1.0
Li 0	Be 0											B 0	C 0.99	N 0	O 1.0	F 0	Ne 1.0
Na 0	Mg 0.90											Al 0	Si 0.95	P 0	S 0.99	Cl 0	Ar 1.0
K 0	Ca 1.0	Sc 0	Ti 0.87	V 0	Cr 0.90	Mn 0	Fe 0.98	Co 0	Ni 0.99	Cu 0	Zn 0.96	Ga 0	Ge 0.92	As 0	Se 0.92	Br 0	Kr 0.89
Rb 0	Sr 0.93	Y 0	Zr 0.89	Nb 0	Mo 0.75	Tc 0	Ru 0.70	Rh 0	Pd 0.78	Ag 0	Cd 0.75	In 0	Sn 0.83	Sb 0	Te 0.92	I 0	Xe 0.52
Cs 0	Ba 0.82	Lu 0	Hf 0.68	Ta 0	W 0.86	Re 0	Os 0.82	Ir 0	Pt 0.66	Au 0	Hg 0.70	Tl 0	Pb 0.78	Bi 0	Po 0	At 0	Rn 0
Fr 0	Ra 0																
		La 0	Ce 1.0	Pr 0	Nd 0.80	Pm 0	Sm 0.71	Eu 0	Gd 0.70	Tb 0	Dy 0.56	Ho 0	Er 0.77	Tm 0	Yb 0.70		
		Ac 0	Th 1.0	Pa 0	U 0.99	Np 0	Pu 0	Am 0									

Spin-lattice relaxation T_1

- For a spin in vacuum, relaxation from blackbody environment

Spin-lattice relaxation T_1

- For a spin in vacuum, relaxation from blackbody environment, $T_1 \sim 10^{13}$ years at 10 MHz

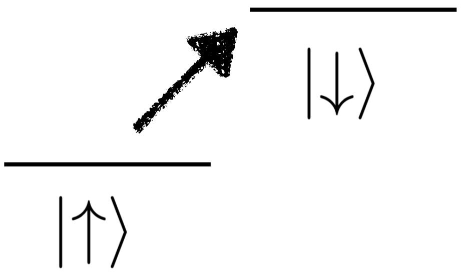
- In a solid, phonons can induce relaxation

spin-lattice = spin-orbit + orbital-lattice

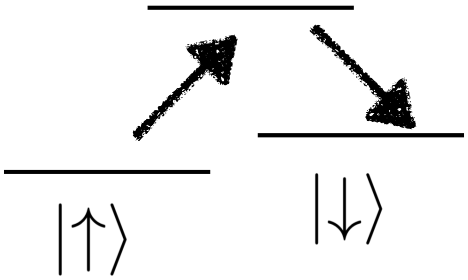
=> want light atoms, stiff lattice

Mechanisms

- Direct process, linear in T



- Orbach process, exponential with T



- Raman process, T^n