Diamond Quantum Devices

Sensing, Simulation and Biology

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Diamond Defects as Quantum Spin Sensors

Working Principle:
Optically Detected Magnetic Resonance

- Sensor measures magnetic field
- Optical readout of single atom sensor

Atomic Spin

Crystals are like people, its only the defects that make them interesting F. Franck

Doherty, Manson, Delaney, Jelezko, Wrachtrup, Hollenberg, Phys. Rep. 2013

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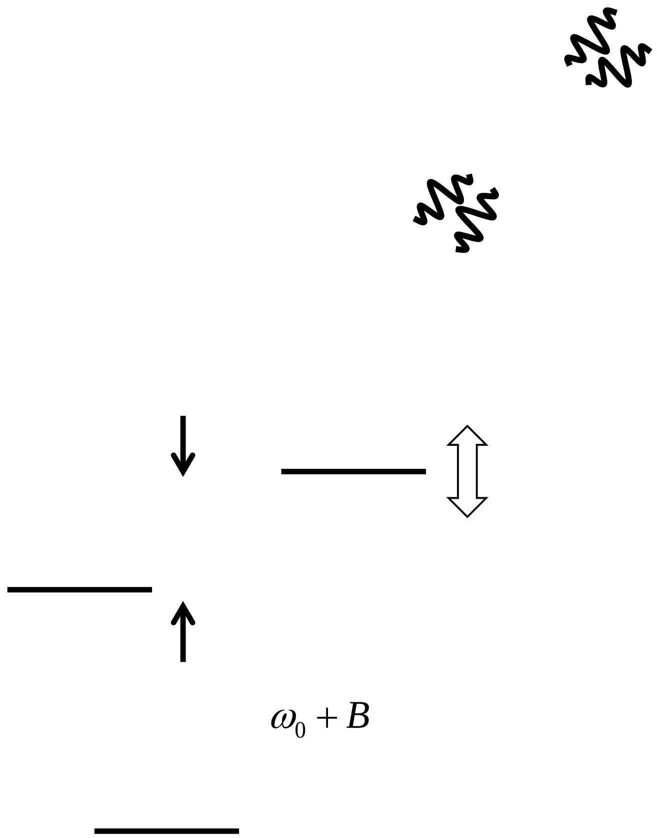
Protecting against Noise

Environmental fluctuations possess finite memory time

⇨ Employ dynamical decoupling techniques

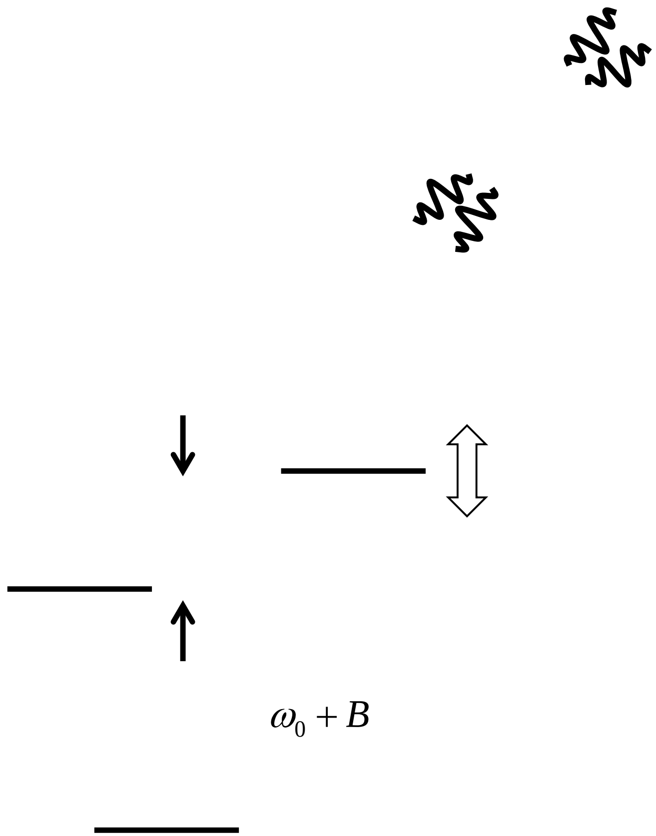


Magnetic field defines two-level system

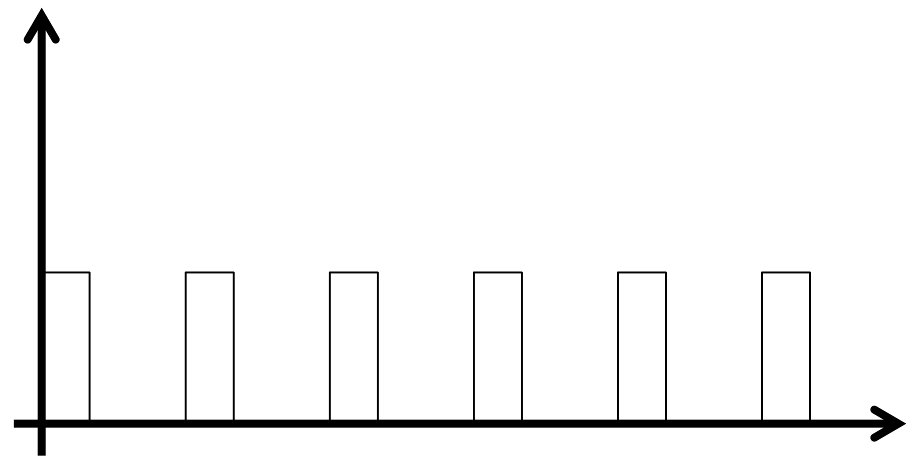
Protecting against Noise

Environmental fluctuations possess finite memory time

Employ dynamical decoupling techniques

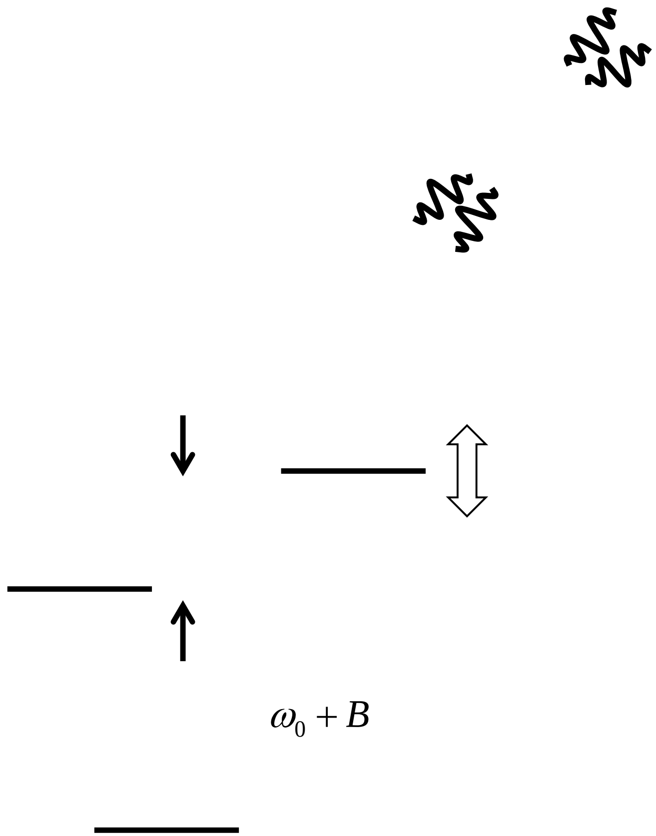


Magnetic field defines two-level system



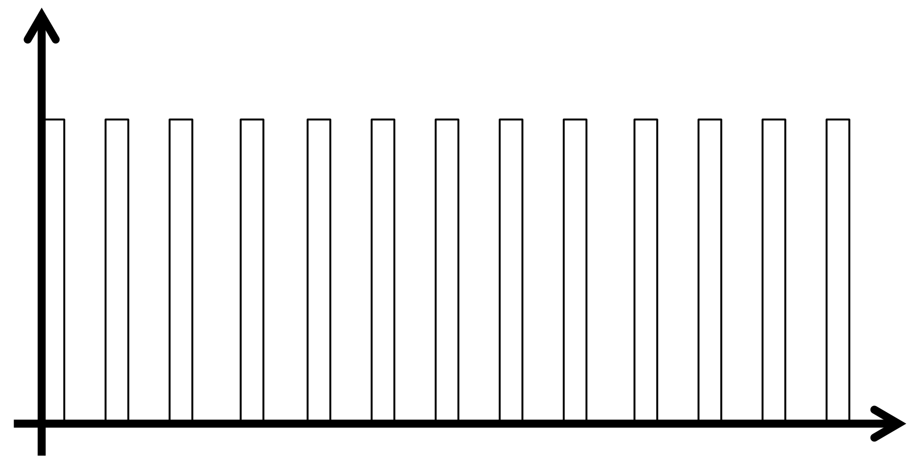
Pulsed decoupling – Induce short π-pulses to average out interaction with the environment

Protecting against Noise



Environmental fluctuations possess finite memory time

⇒ Employ dynamical decoupling techniques



Magnetic field defines two-level system

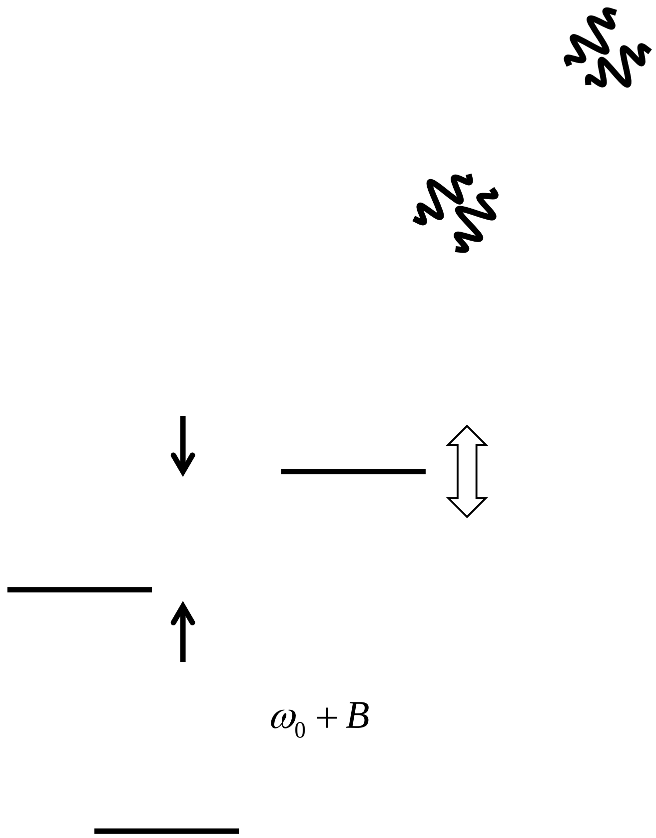
Pulsed decoupling – Induce short π-pulses to average out interaction with the environment

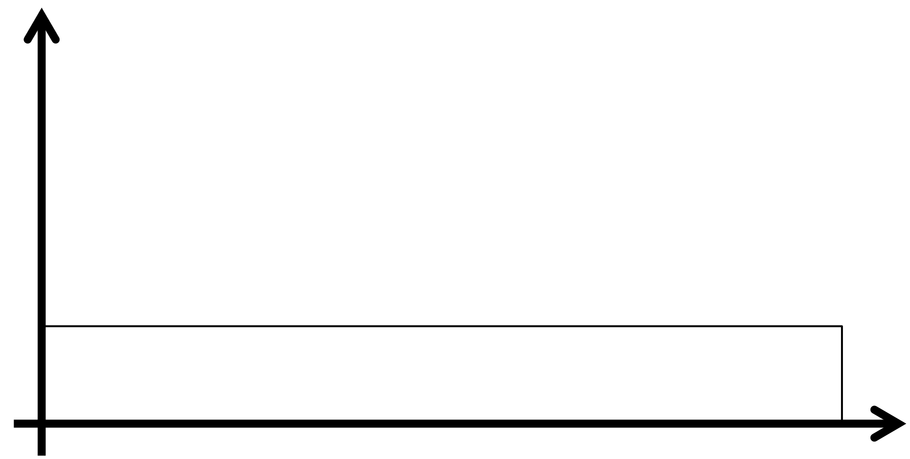
Increase pulse rate to improve decoupling

Protecting against Noise

Environmental fluctuations possess finite memory time

⇒ Employ continuous dynamical decoupling techniques



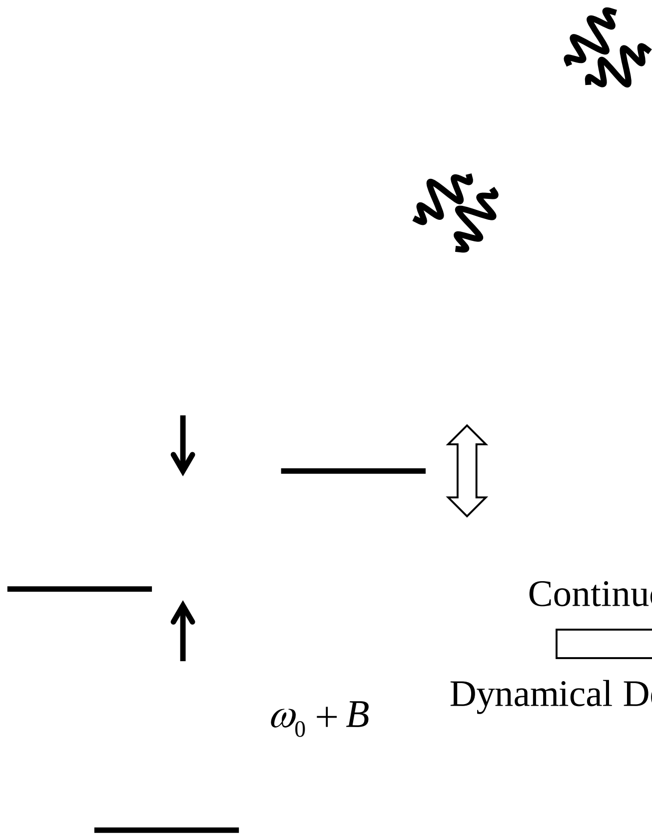


Magnetic field defines two-level system

Protecting against Noise

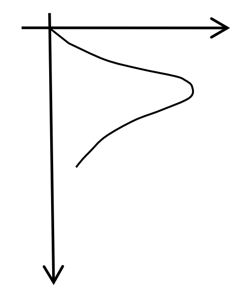
Environmental fluctuations possess finite memory time

⇒ Employ continuous dynamical decoupling techniques



Continuous ⇒ Dynamical Decoupling

Environment spectral density

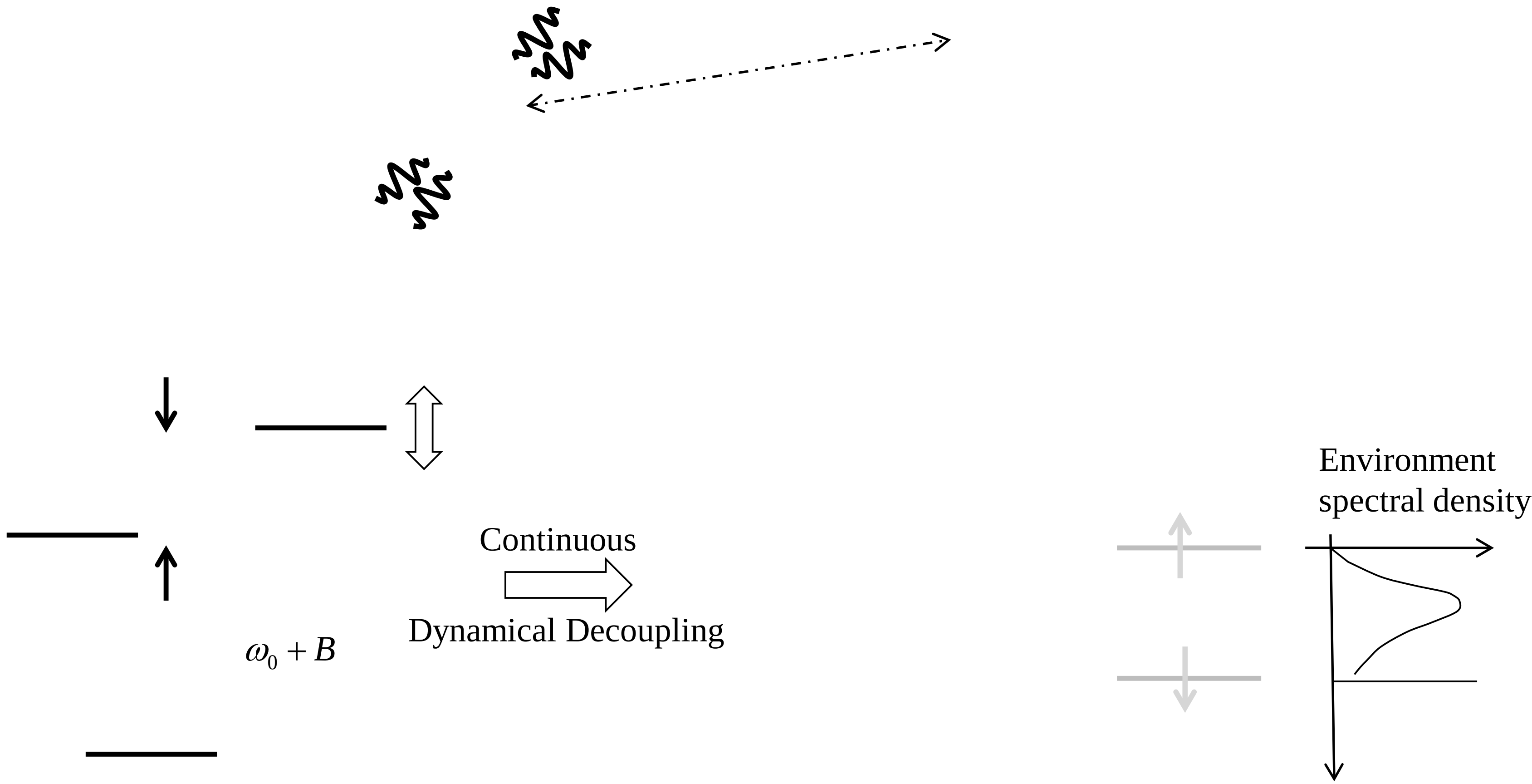


Magnetic field defines two-level system

Interaction with environment carries energy penalty

NJP **15**, 013020 (2013)

Protecting against Noise



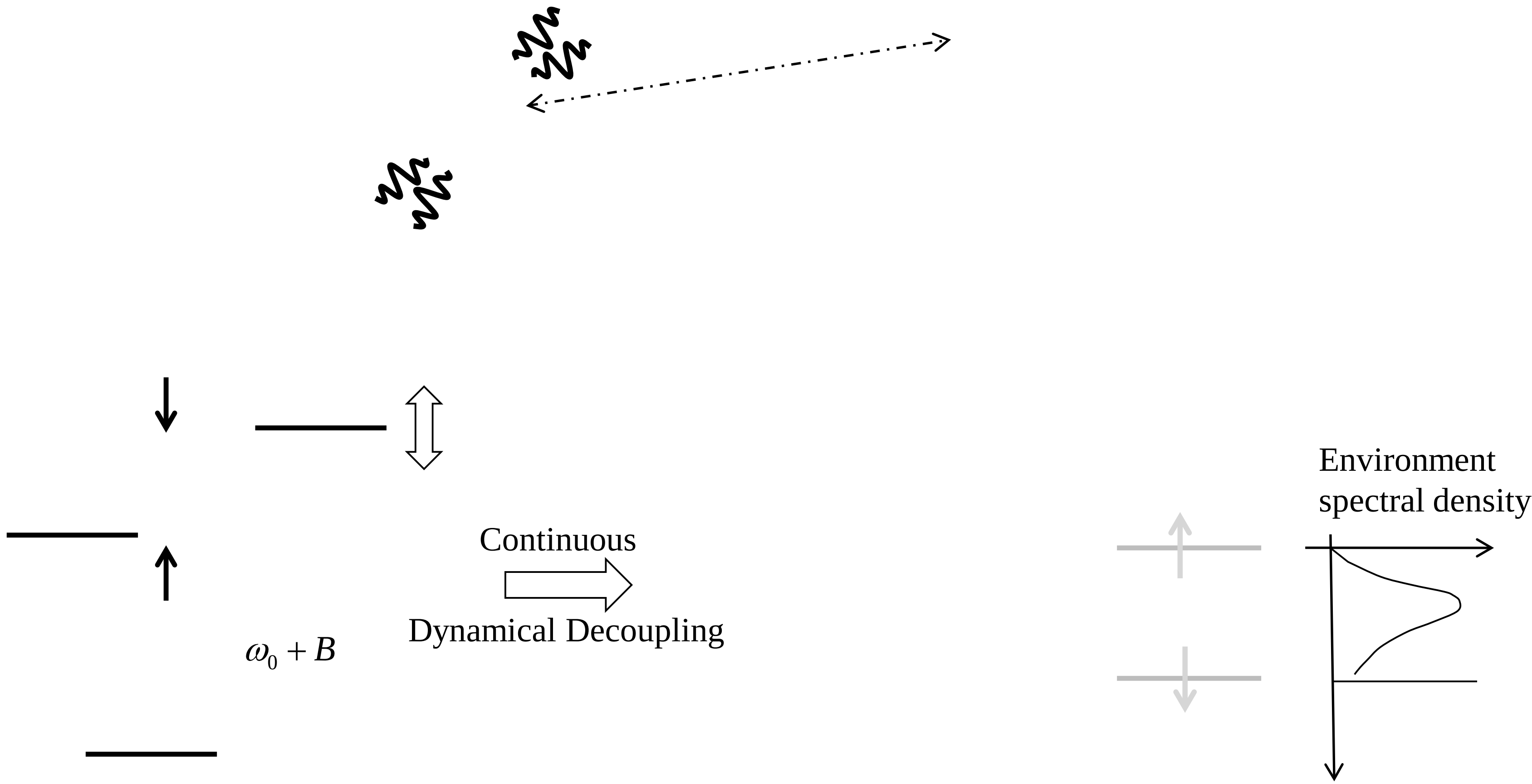
Magnetic field defines two-level system

Hartmann-Hahn condition (1962)

Interaction with environment
carries energy penalty

NJP **15**, 013020 (2013)

Protecting against Noise



Magnetic field defines two-level system

Hartmann-Hahn condition (1962)

Interaction with environment
carries energy penalty

NJP **15**, 013020 (2013)

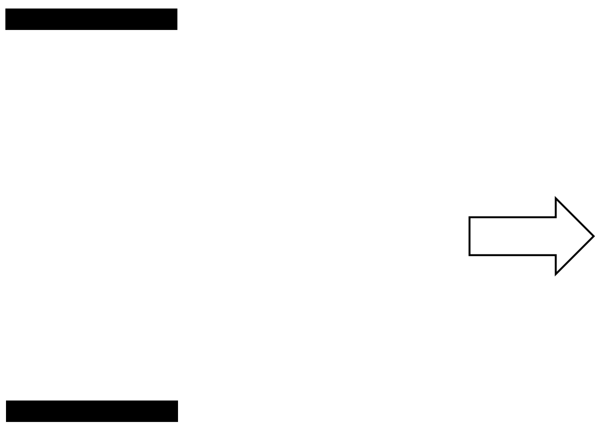
The Sensor in Action

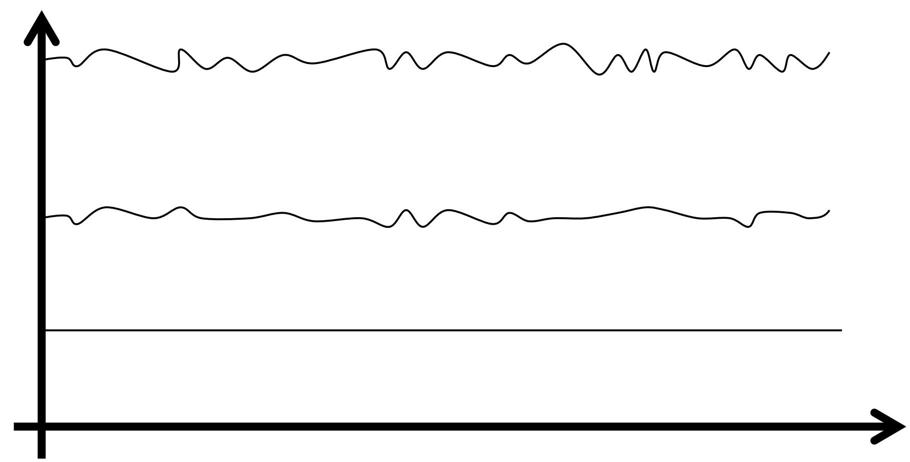
- Measurement on NV spin

Phosphoric acid

Theory: NJP **15**, 013020 (2013) & Experiment: PRL **111**, 067601 (2013)

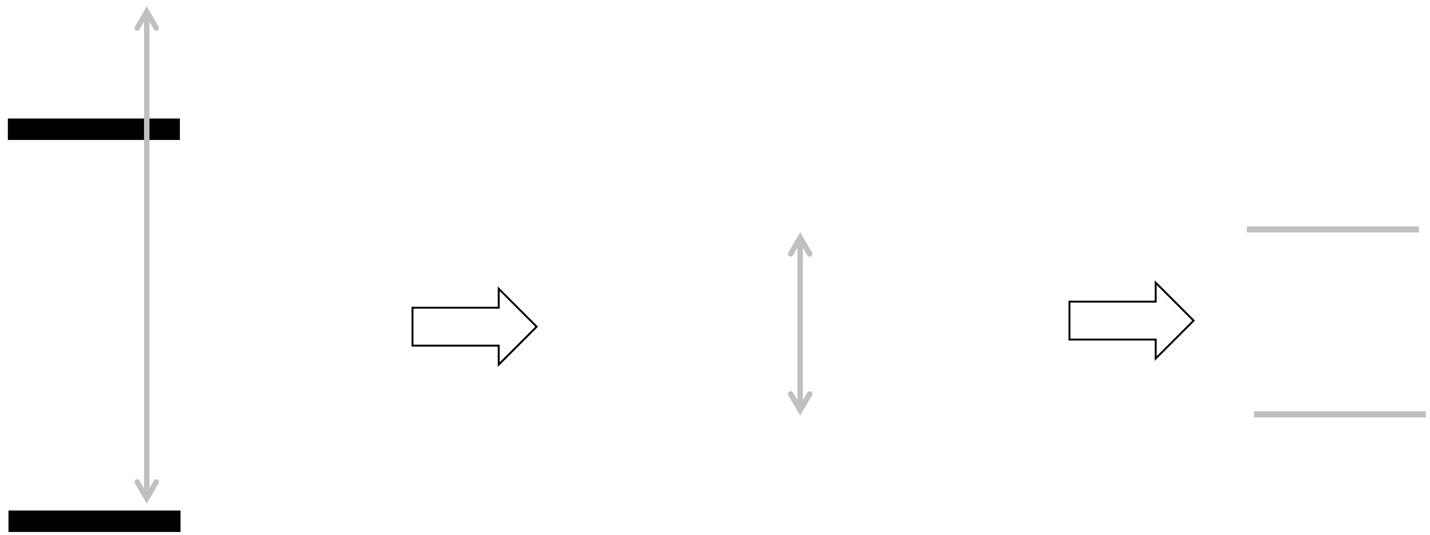
Concatenated Noise Protection

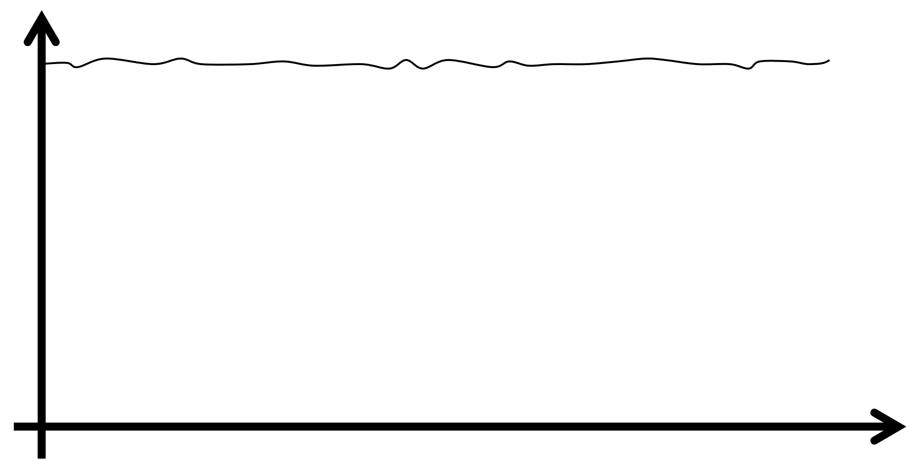




Theory & Experiment: NJP **14**, 113023 (2012).

Concatenated Noise Protection





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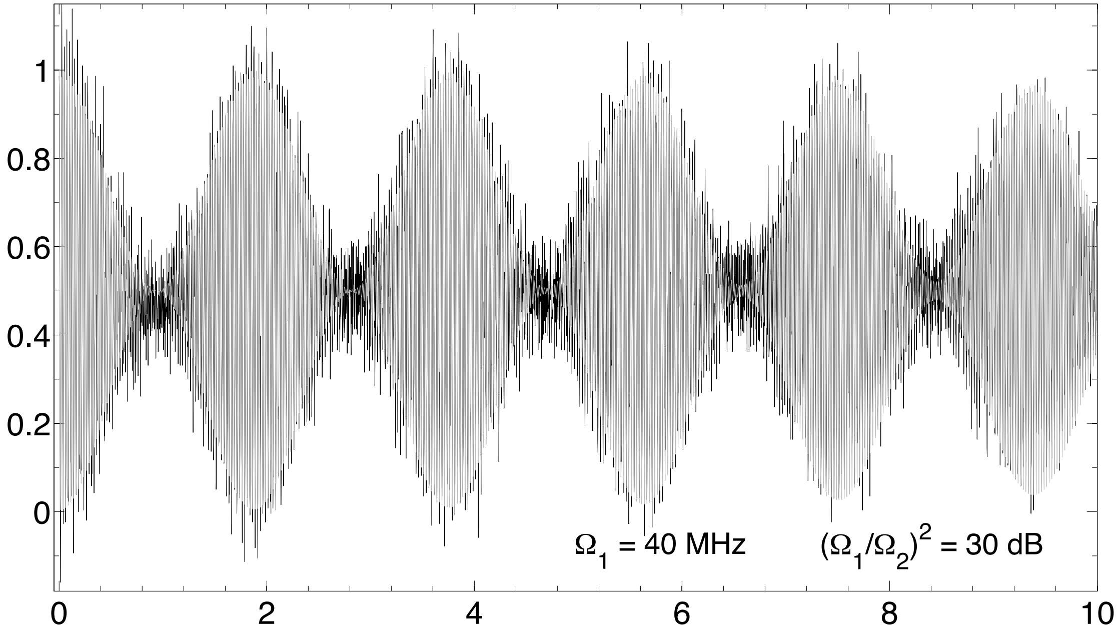
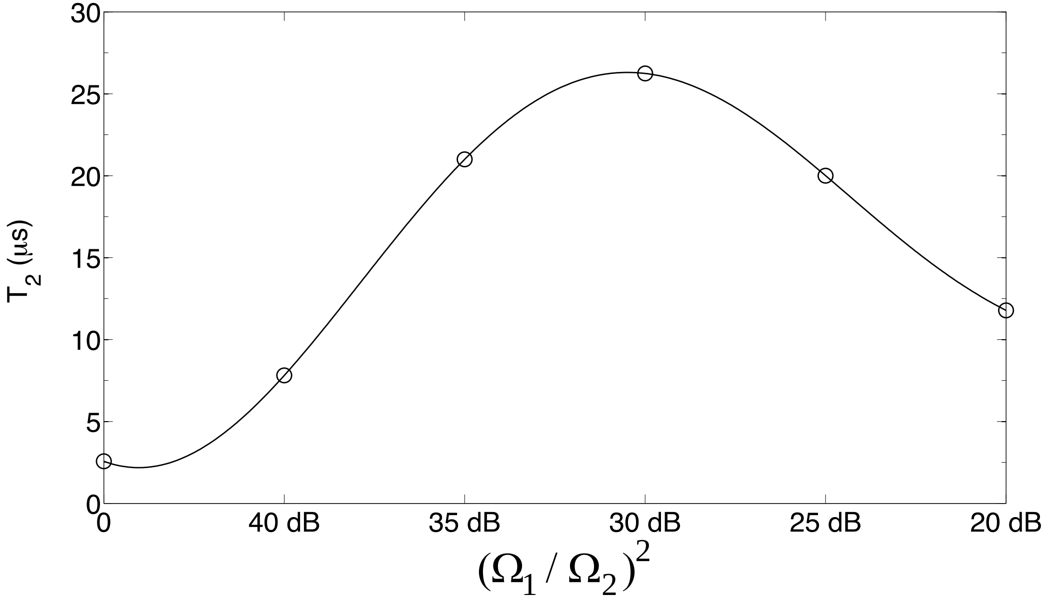
Concatenated Noise Protection





Theory & Experiment: NJP **14**, 113023 (2012).

Other Applications

Theory: PRA 85, 040302 (2012)

Theory: PRL 107, 150503 (2011)

Experiment Wineland et al Phys. Rev. Lett. 110, 263002 (2013)

Theory & Experiment: Nature 476, 185 (2011)
Gate with 2s coherence time
Theory & Experiment: E-print arXiv:1411.7893
Sensor with

Theory: Nat. Phys. 9, 168 (2013)

Bringing the Sensor to the Biology

Diamonds in Biology

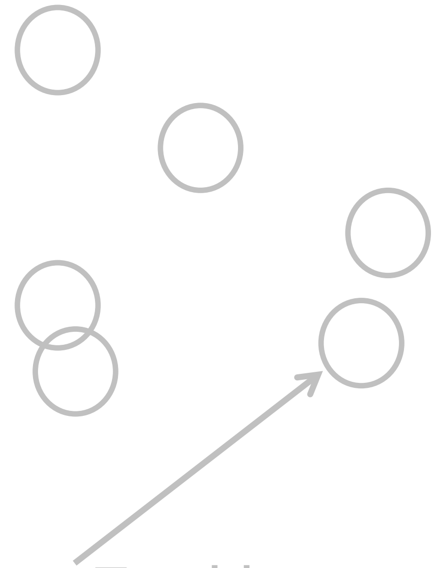
in vitro

Experiment & Theory: Nano Letters **13**, 3305 (2013)

in vivo

Sensing Individual Proteins

Medical Diagnostic Tool



Ferritin

4500 Fe ions (spins) per molecule

Detectable magnetic signal

Ferritin stores iron in our bodies.

→ Malfunction leads to disease.

Experiment & Theory: Nano Letters **13**, 3305 (2013)

Biology for Quanta

Selfassembled Biological Structures

Robin Ghosh

Biology for Quanta

Nanodiamond – Protein Assembly

Experiment & Theory: NJP 16, 093002 (2014)

A Diamond Surface Simulator

Diamond 111-surface

F-F (long range dipole) interaction (6.8kHz nearest neighbor)

Fluorographene

Diamond 100-surface

A Diamond Surface Simulator

Address three main challenges

- Initialization of the nuclear spin lattice
- Control of the Hamiltonian of the nuclear spin lattice
- Readout from the nuclear spin lattice

Theory: Nature Phys. **9**, 168 (2013)

A Diamond Surface Simulator

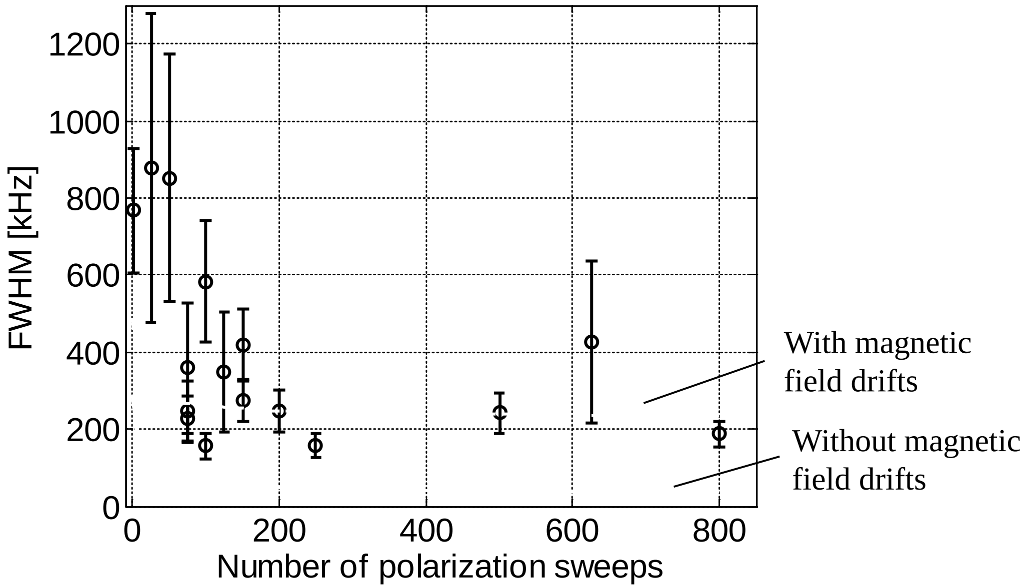
Theory: Nature Phys. **9**, 168 (2013)

Cooling and State Preparation

Polarization of nuclear spin bath reduces linewidth due to T2 time

Numerical simulation shows polarization after 500 sweeps of closest 10% of nculear spins randomly placed in 4nm radius from NV.

Theory & Experiment: PRL 111, 067601 (2013)



Adiabatic preparation of ground state

Cai, Retzker, Jelezko, Plenio, Nat. Phys. 9, 168 (2013)

Sensing Silicon Nuclear Spins on a Diamond Surface

Experiment & Theory: Nat. Comm. 5, 4703 (2014)

Sensing Silicon Nuclear Spins on a Diamond Surface

Experiment & Theory: Nat. Comm. 5, 4703 (2014)

Sensing Silicon Nuclear Spins on a Diamond Surface

Silicon on Diamond Surface

SiO_2 Diluted spin lattice 4.67 % of ^{29}Si

Si-Si distance: a = 0.306 nm

Coupling to closest NV – 1-10 kHz

Coupling between ^{29}Si nuclear spins – 0.1 kHz

⇨ **Field fluctuations from ~9 Si^{29}**
5 nm^3 spatial resolution

Experiment & Theory: Nature Communications 5, 4703 (2014)

Sensing Silicon Nuclear Spins on a Diamond Surface

Signal Processing Methods

Extract nuclear spins information by basis pursuit such as

Measured data

Filter functions

1-norm minimization favors low rank solutions

Experiment & Theory: Nature Communications 5, 4703 (2014)

Diamond Surfaces

Sensing Pressure and Forces

periodic strain

Theory: New J. Phys. **15**, 083014 (2013)

Diamond Surfaces

Sensing Pressure and Forces

NV-center in diamond:

Diamond Surfaces

Sensing Pressure and Forces

NV-center in diamond:

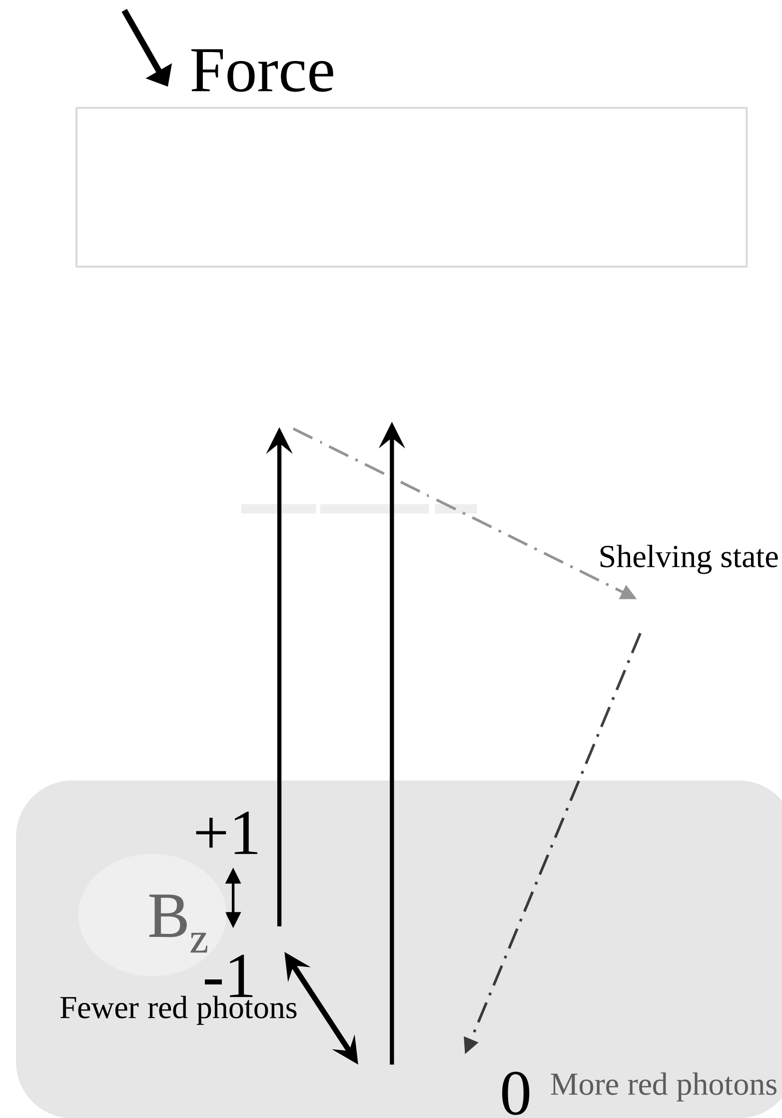
NV-center in Terfenol-diamond:

Theory: Nature Comm. **5**, 4065 (2014) & International Patent Application PCT/EP2014/057788

Diamond Hybrid Sensor

Hard Diamond – Piezomagnetic Material

+ “Soft”



- ✓ Force induced deformation (magnetization)
- ✓ Stray magnetic field detected by the NV spin sensor

Theory: Nature Comm. **5**, 4065 (2014) & International Patent Application PCT/EP2014/057788

Diamond Surfaces

Sensing Pressure and Forces

Force sensitivity:

Theory: Nature Comm. **5**, 4065 (2014) & International Patent Application PCT/EP2014/057788

Institute
of Theoretical Physics

Synergy Grant:
Diamond Quantum
Devices and Biology

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EQUAM

CO.CO.MAT