Robust Control in RF-Optical Double Resonance Experiments

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The Team

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APPRAOCH TO HIGH-RESOLUTION nmr IN SOLIDS

J. S. Waugh, L. M. Huber, and U. Haeberlen†
Department of Chemistry and Research Laboratory of Electronics,
Massachusetts Institute of Technology, Cambridge, Massachusetts 02139
(Received 27 December 1967)
NMR Population Inversion Using a Composite Pulse

MALCOLM H. LEVITI
RAY FREEMAN

RF Inhomogeneity

Resonance offset
Larger Systems

Before: 2 levels

Spin 1/2

$^1\text{H}$

Spin 1

$^2\text{D}$

3 levels

1984@Zürich

Composite pulse excitation in three-level systems

M. H. Levitt, D. Suter, and R. R. Ernst

Multiple Spins
Multiple Interactions

Broadband Heteronuclear Decoupling in the Presence of Homonuclear Dipolar and Quadrupolar Interactions

K. V. Schenker, D. Suter, and A. Pines

Decoupler offset
Quantum Control = Teaching spins new tricks

... even in the presence of distraction
NMR Quantum Computing

Spins inside

Quantum processor

Nuclear spins
I = 1/2

|1⟩

|0⟩
Liquid state NMR is an excellent system for small quantum registers.

e.g. Simulation of Quantum Phase Transition

\[ \langle \sigma_1^z \rangle^2 \]

Magnetic field \( B_z \)

Liquids NMR

Main problem: couplings are weak (~10 Hz)

Liquids are simple, easy to handle

Liquid Crystal NMR

Stronger couplings in liquid crystals: ~ 1 kHz
Dipolar Coupled System

How do we implement quantum gates?

Reference spectrum

Table:

<table>
<thead>
<tr>
<th></th>
<th>H1</th>
<th>H2</th>
<th>H3</th>
<th>H4</th>
</tr>
</thead>
<tbody>
<tr>
<td>H1</td>
<td>-303.7</td>
<td>7.7</td>
<td>0.8</td>
<td>3.1</td>
</tr>
<tr>
<td>H2</td>
<td>-788.0</td>
<td>-3.5</td>
<td>7.6</td>
<td>8.0</td>
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<tr>
<td>H3</td>
<td>85.7</td>
<td>-278.5</td>
<td>-208.1</td>
<td>7.4</td>
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<tr>
<td>H4</td>
<td>71.0</td>
<td>-667.2</td>
<td>-1873.4</td>
<td>-248.3</td>
</tr>
</tbody>
</table>

Dipolar couplings $d_{ij}$, Ref. spectrum
Gate Operations

e.g. State Preparation (POPS)

\[ [0 / \pi]^{(2)} G_z \]

[Diagram of spectral lines and state transitions]

Not possible for all transitions

Reference: hard pulse excitation

Custom shaped pulses
Classical gradient estimation requires $\geq d+1$ function evaluations in $d$ dimensions.

Quantum gradient estimation requires 1 function evaluation.

Here: $d = 1$

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Classical gradient estimation diagram:

- For $d=1$, a line segment.
- For $d=2$, a line segment with a dot.
- For $d=3$, a line segment with two dots.

Quantum gradient estimation diagram:

1. Input register.
2. Ancilla register.
3. QFT block.
4. IQFT block.
5. $U_f$ block.
6. $H$ block.

References:

Optimized Sequence

Total duration 3.5 ms

Resulting populations

Theory

Experiment

Result: Input qubits = |10⟩

∇f = 2
Robustness

RF inhomogeneity

H Signal

Pulse duration / ms

0 100

1H Signal

13C Signal

Pulse duration / ms

0 200 400

Fidelity

Scalability and Decoherence

Decoherence

Main source: coupling to environment
Decoherence

NMR Signal

FID = Free Induction Decay

Relaxation = Decoherence

observable magnetization = single qubit coherence

Quantum register involves coherence of many qubits

How fast will a “useful” quantum register loose information?
Scaling of Decoherence

Needed for factorization

More Data

WANTED!

available experimental data (liquids NMR)

Needed for factorization
Model quantum register with 1000's of nuclear spin qubits
Thermal equilibrium: independent spins

Use dipole-dipole couplings to correlate spins

Quantum control
Multiple pulses

pumping time
Observed Decays

Normalized signal $s_{\text{FID}}$ vs. $t_1$ in microseconds ($\mu$s)

- **FID**
- Single spin decoherence

- Bigger systems decay more rapidly

- 26 spins
- 189 spins
- 650 spins
- 3555 spins
Decoherence Rates

Decoherence rate \([\text{ms}^{-1}]\]

Number of correlated spins \(\overline{K}\)

\(\approx \sqrt{K}\)
Can We Reduce Decoherence?

Goal:

Bath

Idea: modulate coupling with bath

long-lived coherence

average = 0
Decoupling Quantum Registers

Yes, we can!

Decoherence rate \([\text{ms}]^{-1}\) vs. Quantum register size \(\bar{K}\)

- Free evolution
- Decoupled

PRL 97, 150503 (2006)
$^{141}\text{Pr} : I = 5/2$

$\lambda = 610 \text{ nm}$

$^1\text{D}_2$

$^3\text{H}_4$

0.9 MHz

7.1 MHz

Pr:YAlO$_3$
$^{141}\text{Pr} : I = 5/2$

Spin Transitions

NMR frequency / MHz

0.9 MHz

7.1 MHz

NMR frequency / MHz

1 - $\frac{1}{2}$

3 - $\frac{3}{2}$
CW (exp.)

Pulsed excitation

Optimized pulsed excitation

Frequency / MHz
Range covered by single 2D experiment
Pulsed Excitation

\[ \lambda = 610 \text{ nm} \]

\[ 1^D_2 \]

\[ \omega_e \]

\[ \omega_L \]

\[ \omega_g \]

0.9 MHz

7.1 MHz

\[ 3^H_4 \]
Composite Laser Pulses

Photon Echo

π-Pulse

Offset-compensated π-pulse

— Spectral hole

<table>
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<th>Pump-pulse type ( FWHH )</th>
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</thead>
<tbody>
<tr>
<td>a) 0.9 MHz</td>
</tr>
<tr>
<td>b) 1.4 MHz</td>
</tr>
<tr>
<td>c) 2.7 MHz</td>
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</tbody>
</table>

— Transmission

<table>
<thead>
<tr>
<th>Probe-laser frequency shift [MHz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>-5</td>
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</table>

— Photon-echo intensity

<table>
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<th>Time [µs]</th>
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