Algorithmic cooling with NV center in diamond

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Jörg Wrachtrup
Sadegh Raeisi
Sebastian Zaiser

- Background
  - challenge in NMR
  - Algorithmic cooling
  - Prediction
- Experiment
  - Brief introduction to Nitrogen-vancancy center (NV center)
  - Implementation of the quantum circuit
  - Results

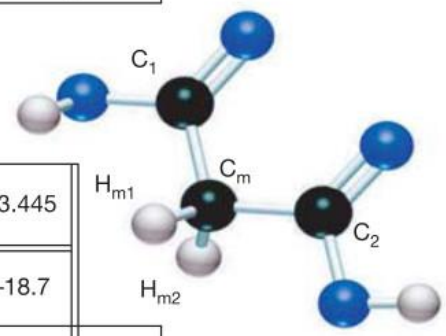
Background

Why algorithmic cooling(AC)?

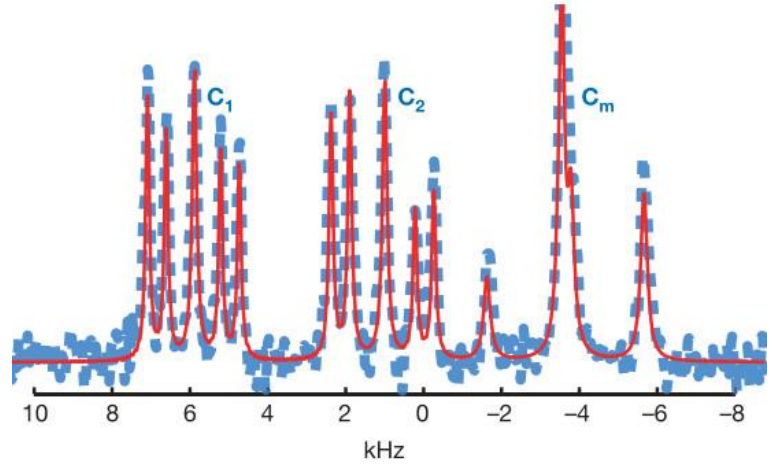
- Define polarization $\epsilon = P_0 - P_1$
- ϵ around 10^{-5} to 10^{-6} in equilibrium[2]
- Low polarization
- Low signal-to-Noise Ratio

- To increase polarization
- To develop high-sensitivity NMR spectroscopy

	C_1	C_2	C_m	H_{m1}
C_1	5.893			
C_2	0.227	1.057		
C_m	0.935	1.070	−3.445	
H_{m1}	−1.5	1.4	−18.7	
H_{m2}	2.0	1.0	−0.9	−22.0

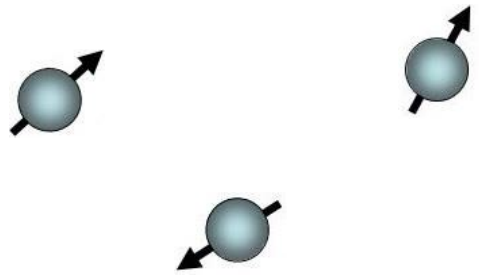


Picture from [1]



[1]J. Baugh, O. Moussa, C. A. Ryan, A. Nayak & R. Laflamme.
Experimental implementation of heat-bath algorithmic cooling using solid-state nuclear magnetic resonance. 24 November 2005|doi:10.1038/nature04272
[2]Jos´e M. Fernandez, Seth Lloyd, Tal Mor & Vwani Roychowdhury.
Algorithmic Cooling of Spins: A Practicable Method for Increasing Polarization. arXiv:quant-ph/0401135v2 23 Jan 2004

How does AC work?



$|000\rangle$

$|001\rangle$

$|010\rangle$

$|011\rangle$

$|100\rangle$

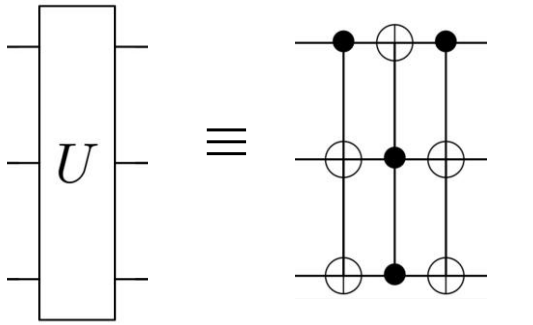
$|101\rangle$

$|110\rangle$

$|111\rangle$

How does AC work?

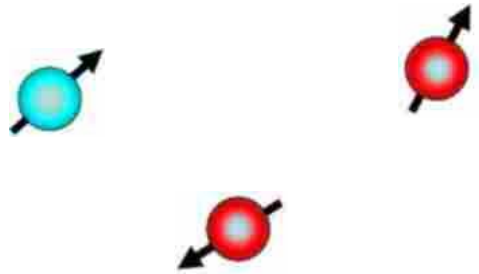
- Increase polarization of 1st nuclear spin by suppressing other two
- Swap $|011\rangle$ & $|100\rangle$



$\equiv$

$\equiv \quad U =$

$$\begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

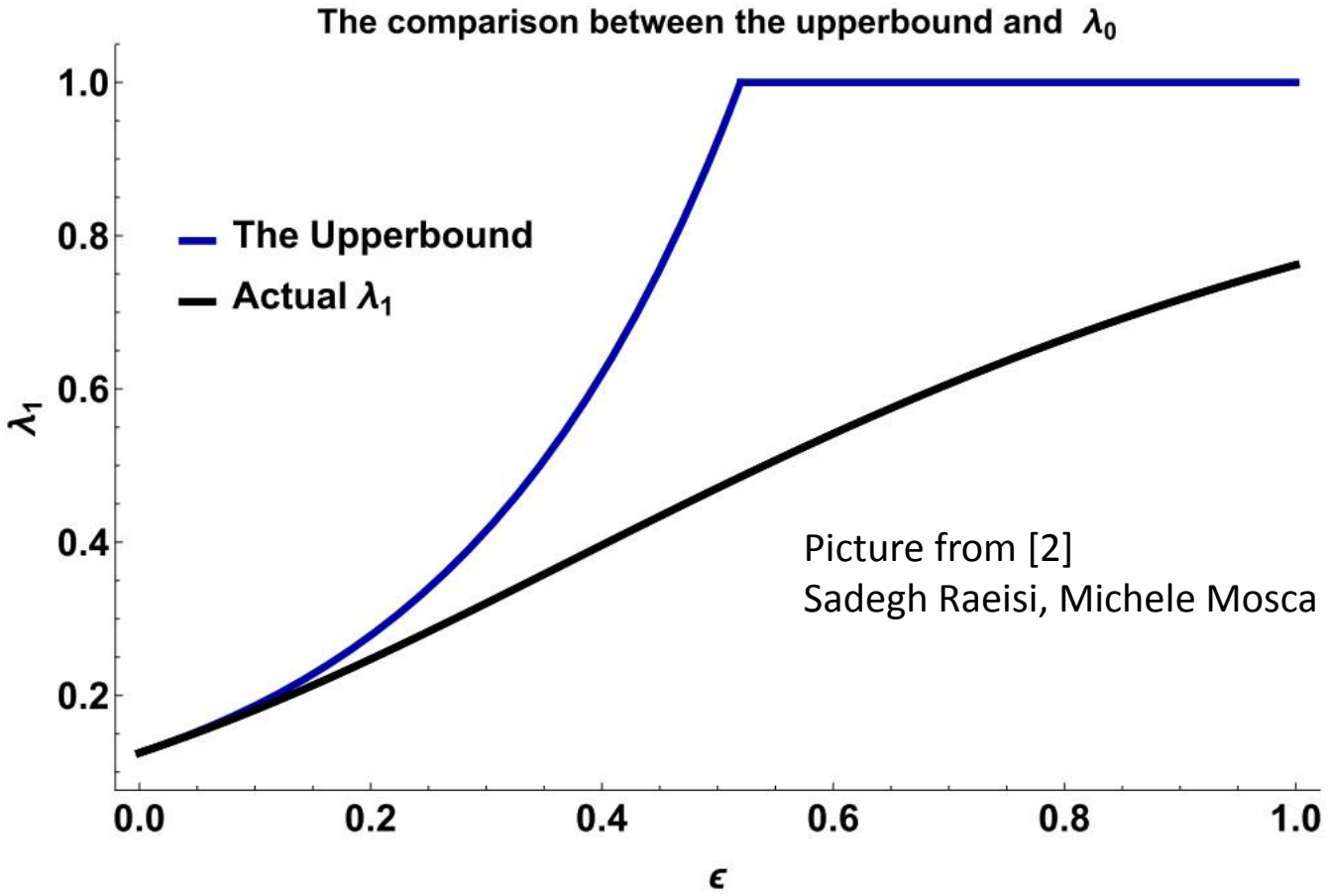


$|000\rangle$
$|001\rangle$
$|010\rangle$
$|011\rangle$
$|100\rangle$
$|101\rangle$
$|110\rangle$
$|111\rangle$

- $\epsilon_{new} = \frac{3}{2}\epsilon - \frac{\epsilon^3}{2}$ [1]
- Tiny enhancement

[1]Jos´e M. Fernandez , Seth Lloyd , Tal Mor , Vwani Roychowdhury. Algorithmic Cooling of Spins: A Practicable Method for Increasing Polarization. arXiv:quant-ph/0401135v2 23 Jan 2004

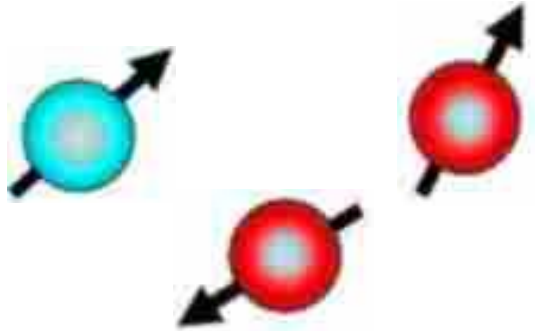
How to get more higher polarization?



Picture from [2]
Sadegh Raeisi, Michele Mosca

Theoretical limit

Potential to fully polarize 1st spin



[1]L. J. Schulman, T. Mor, and Y. Weinstein, Phys. Rev. Lett. 94, 120501 (2005).
[2]Sadegh Raeisi, Michele Mosca. The Asymptotic Cooling of Heat-Bath Algorithmic Cooling. arXiv:1407.3232v2 [quant-ph] 2 Dec 2014

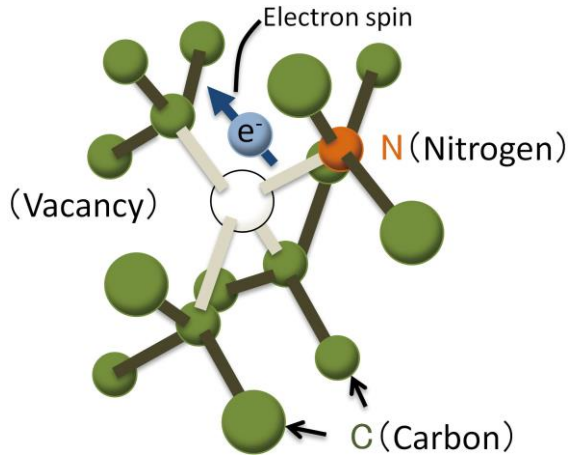
Task

- Demonstrate the method with NV center
- “Proof of principle” experiment
- Verify theory

Experiment

Brief introduction to NV center

- Electron spin
  - Spin dependent optical property:
    - Initialize & readout by laser light
  - Manipulate by microwave (MW)
- Nuclear spin (^{14}N & ^{13}C)
  - Initialize & readout by single-shot-readout method (SSR)
  - Manipulate by radiofrequency (RF)



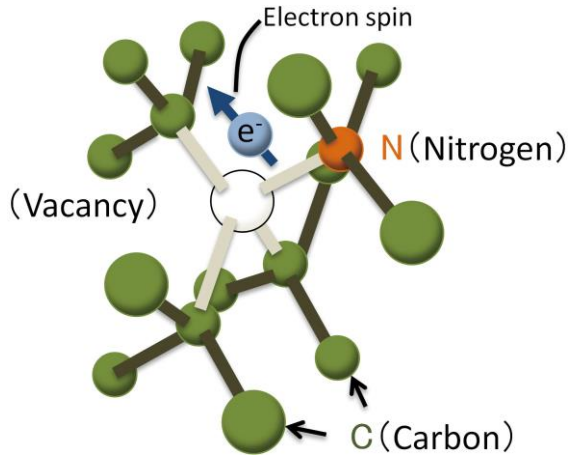
Picture from [1]

e spin : +1, 0, -1
^{14}N spin : +1, 0, -1
^{13}C spin : -1/2, +1/2

[1] KOHEI M. ITOH. Quantum-assisted Sensing Using Nitrogen-vacancy (NV) Centers in Diamond. DOI : 10.22661/AAPPSBL.2015.25.1.12

- To increase the polarization of ^{14}N nuclear spin by suppressing other 2 ^{13}C nuclear spins

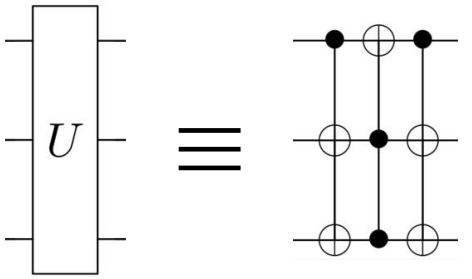
1. Prepare the target 3 nuclear spins into desired polarizations
2. Perform U-gate
3. Reset the 2 ^{13}C nuclear spins into desired polarization
4. Repeat 2 and 3



Picture from [1]

e spin : +1, 0, -1
^{14}N spin : +1, 0, -1
^{13}C spin : -1/2, +1/2

How to realize the U-gate



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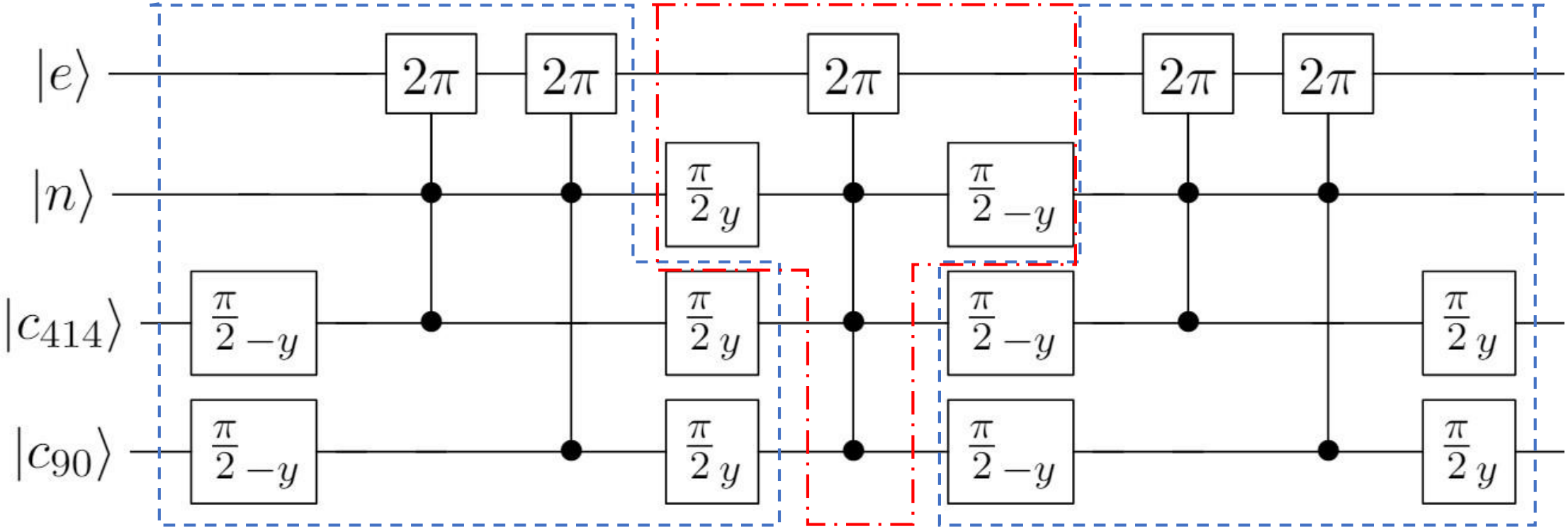
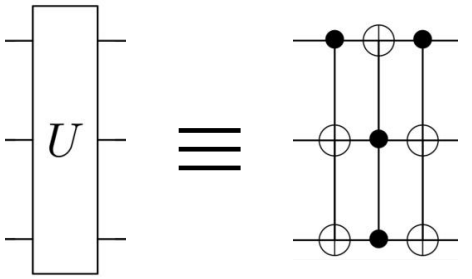
- Electron spin: ancillary Qubit
- ^{14}N, $^{13}C_{414}$, $^{13}C_{90}$ nuclear spins: logical Qubits



How to realize the U-gate



$\equiv$

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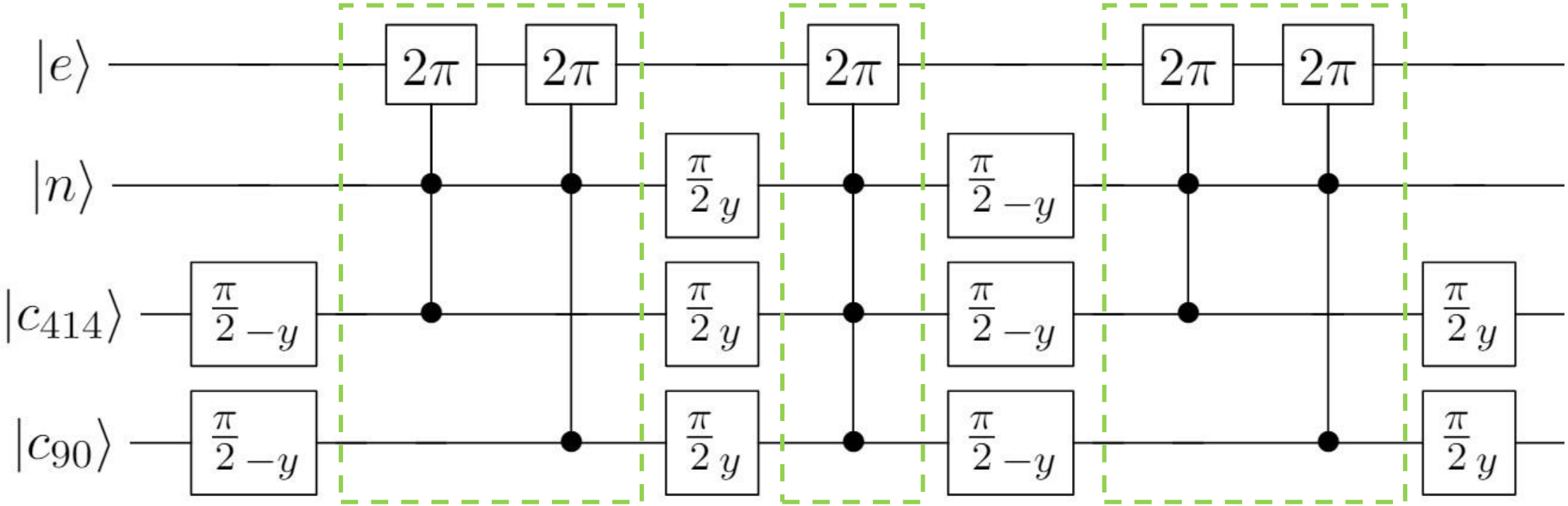
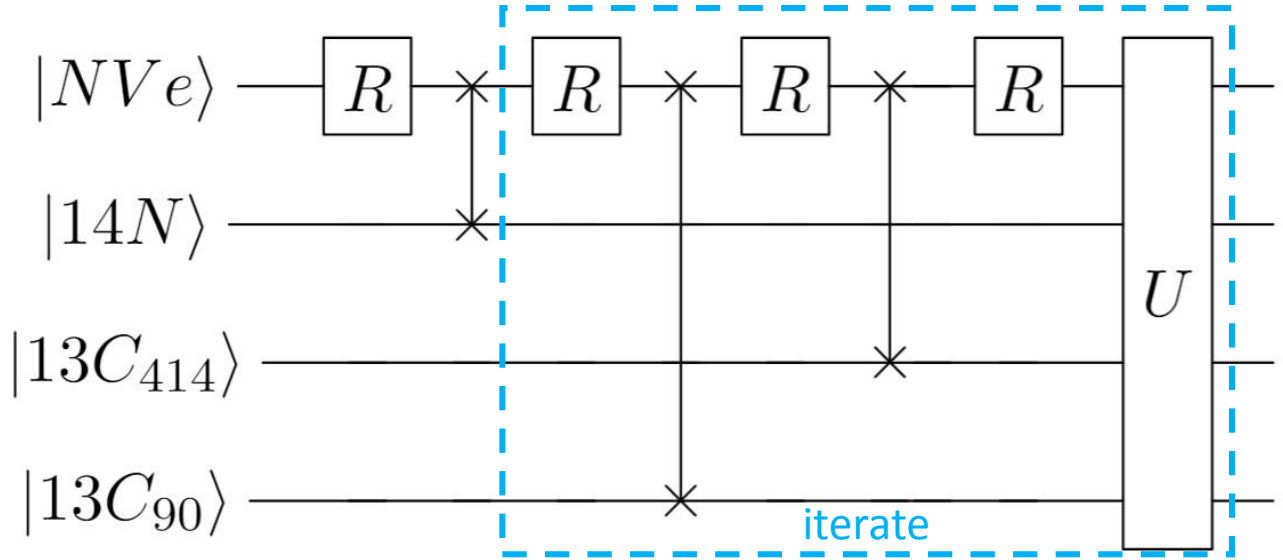
- Performed optimal control for MW parts
  - To avoid driving unwanted transition
  - To increase gate fidelity



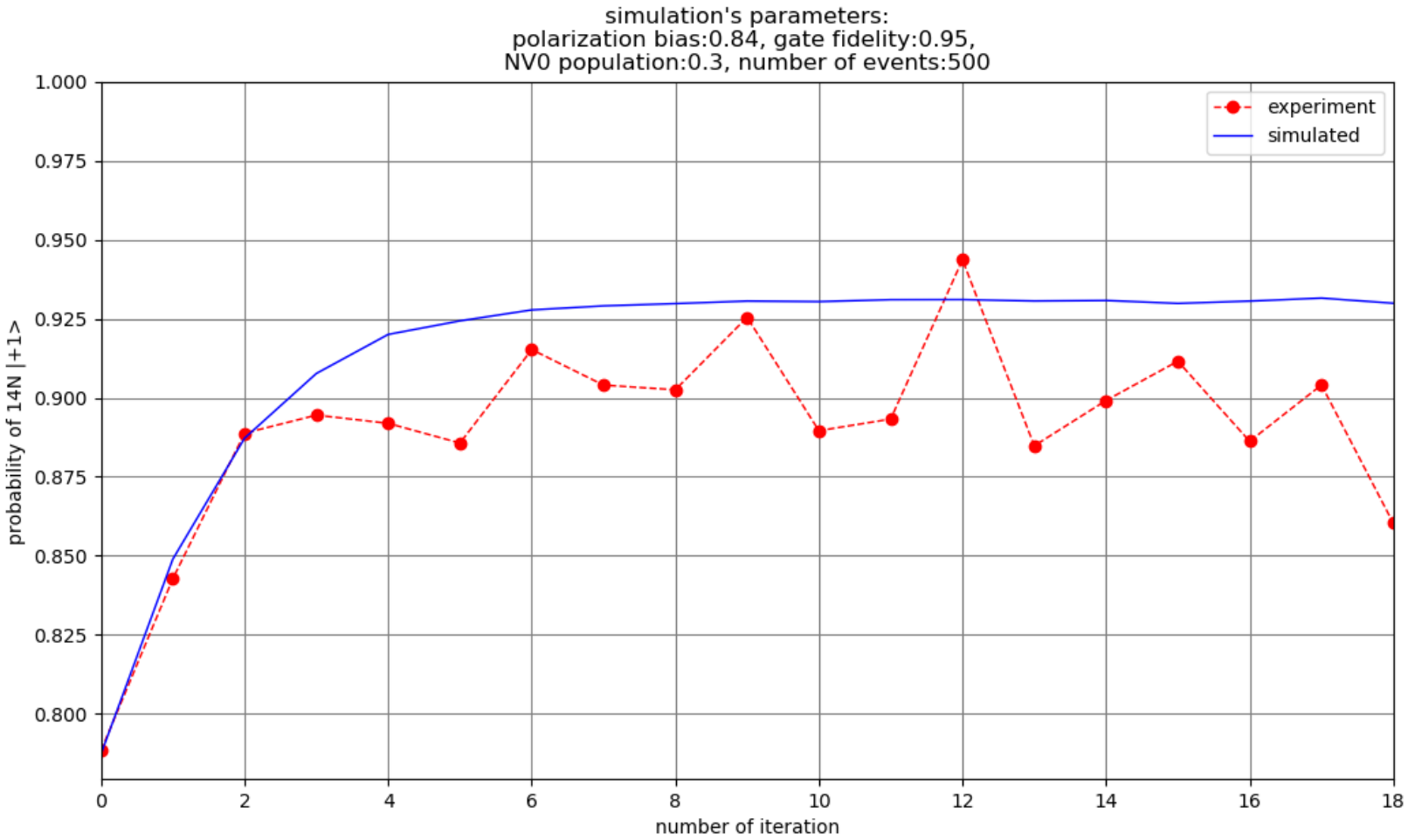
Sequence implemented

- Repolarize: fully
- Swap: partially



- Polarizations of nuclear spins can be prepared to any degree ideally
- Repeat blue boxed part

Result



Initially, Probability in |0>:

^{14}N : ~0.79

$^{13}C_{414}$: ~0.72

$^{13}C_{90}$: ~0.82

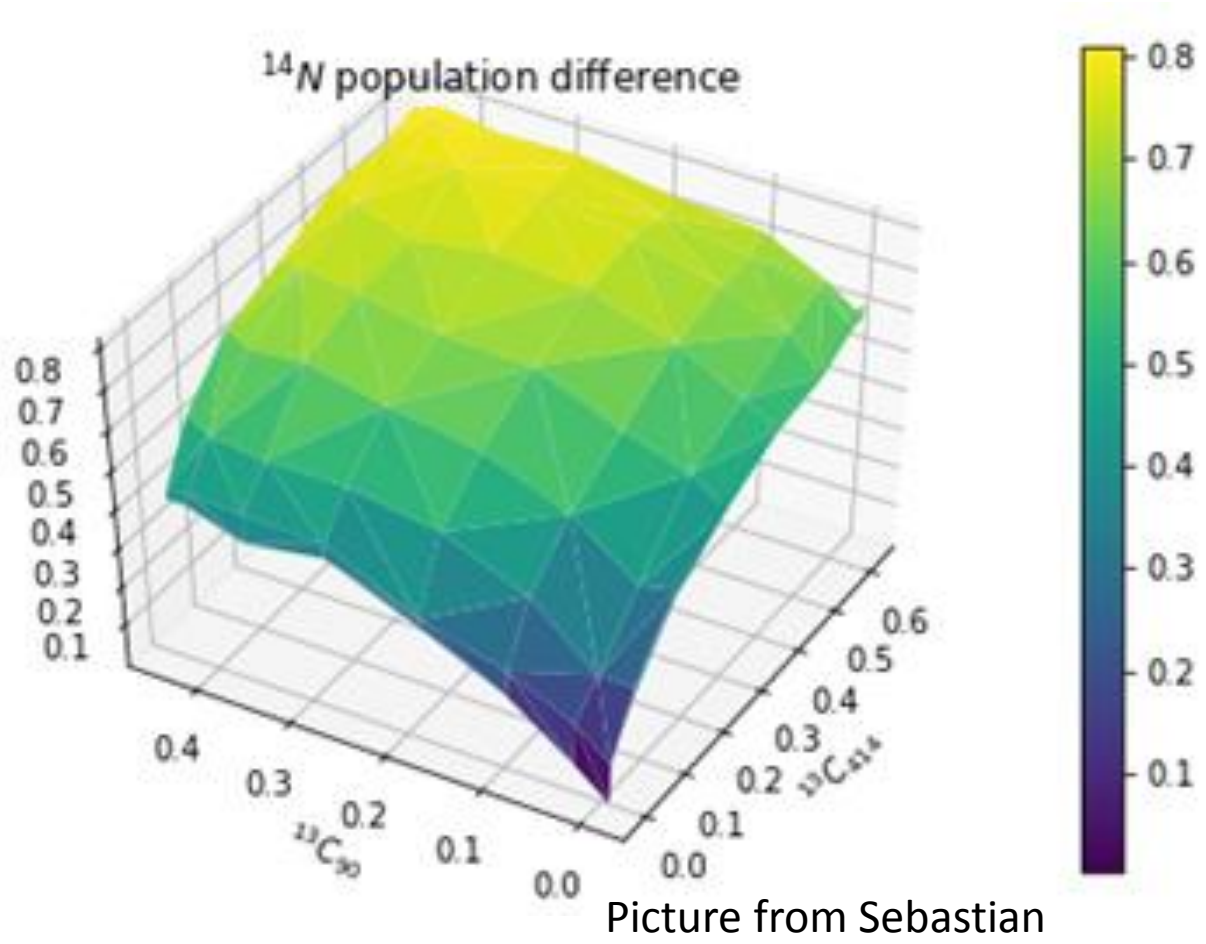
In each iteration,

Probability in |0>:

$^{13}C_{414}$: ~0.72

$^{13}C_{90}$: ~0.82

Vary number of iterations

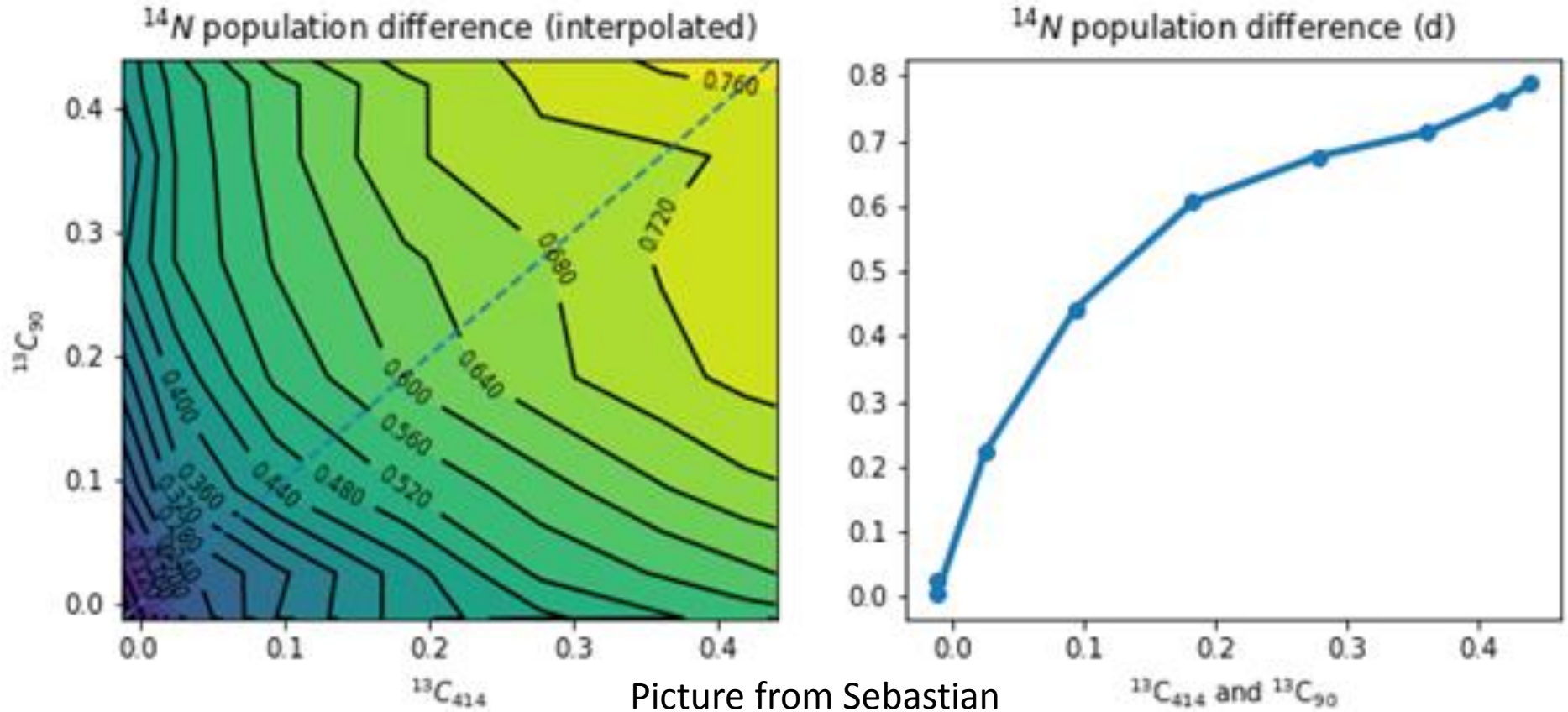


Picture from Sebastian

Initial polarization of $^{14}N = 0$

Iteration number: 25

Vary polarizations of $^{13}C_{414}$ and $^{13}C_{90}$



Picture from Sebastian

Project is ongoing….

- To compare with theory & simulation
- To check the fidelity of the U-gate
- To replace the iteration unit to $\begin{pmatrix} 1 & & & & & & & \\ & 0 & 1 & & & & & \\ & 1 & 0 & & & & & \\ & & & 0 & 1 & & & \\ & & & 1 & 0 & & & \\ & & & & & 0 & 1 & \\ & & & & & 1 & 0 & \\ & & & & & & & 1 \end{pmatrix}$

Q&A