分子スピンを用いた
量子サイバネティクスと
量子コンピュータ
Quantum Cybernetics
and Quantum Computation
using Molecular spins

14 Dec. 2011 Kyoto
FIRSTスピン量子コンピューター
新学術領域量子サイバネティクス分子スピン量子制御
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contents

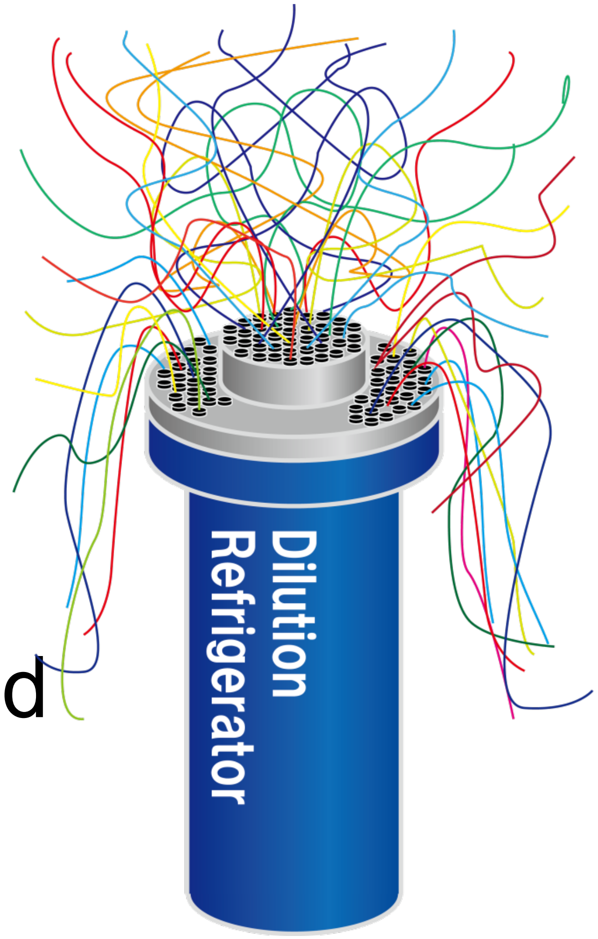
- Global control of quantum information systems (cont'd)
- Ultra precision quantum gate operation (cont'd)
- Fault-tolerant architecture for quantum computation with global control and without measurement (new)
- Scalable spin amplification (cont'd)
- Fast spin amplification (new)

Scalability issue of quantum computer

- How many qubits are available?
  - Are quantum operations still possible?
- Isn't quantum benefit lost?
  - Controls and measurements not exponentially hard
  - Success probability not exponentially decreased?
    - Initialization
    - Fault-tolerance
    - Control-induced decoherence
- Architecture
  - Individual control ←→ Global control

Individual control of spatially addressed qubits

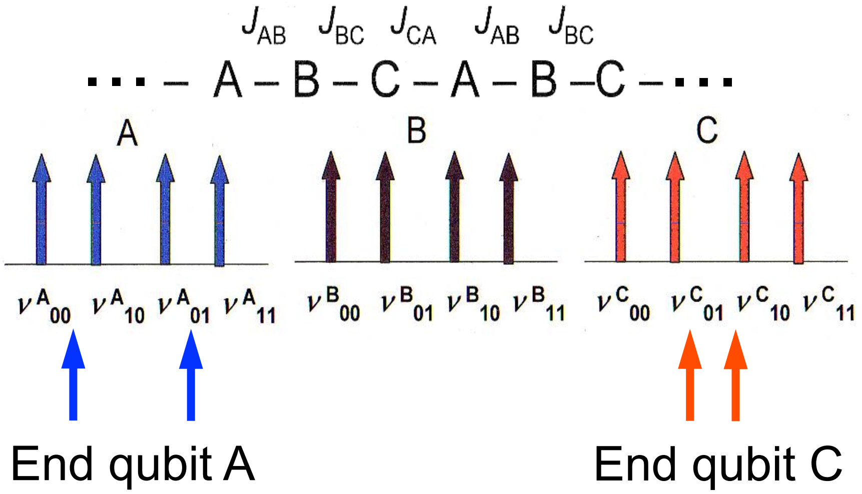
- Spatial addressing
  - Ion trap, quantum dots, superconducting qubits
  - At least one classical control system per qubit
  - Control induced decoherence?
- Spatio-spectral mapping by field gradient
  - At least one frequency per qubit



Global control

A Potentially Realizable Quantum Computer

Seth Lloyd, *Science* Vol. 261, 1569 (1993)

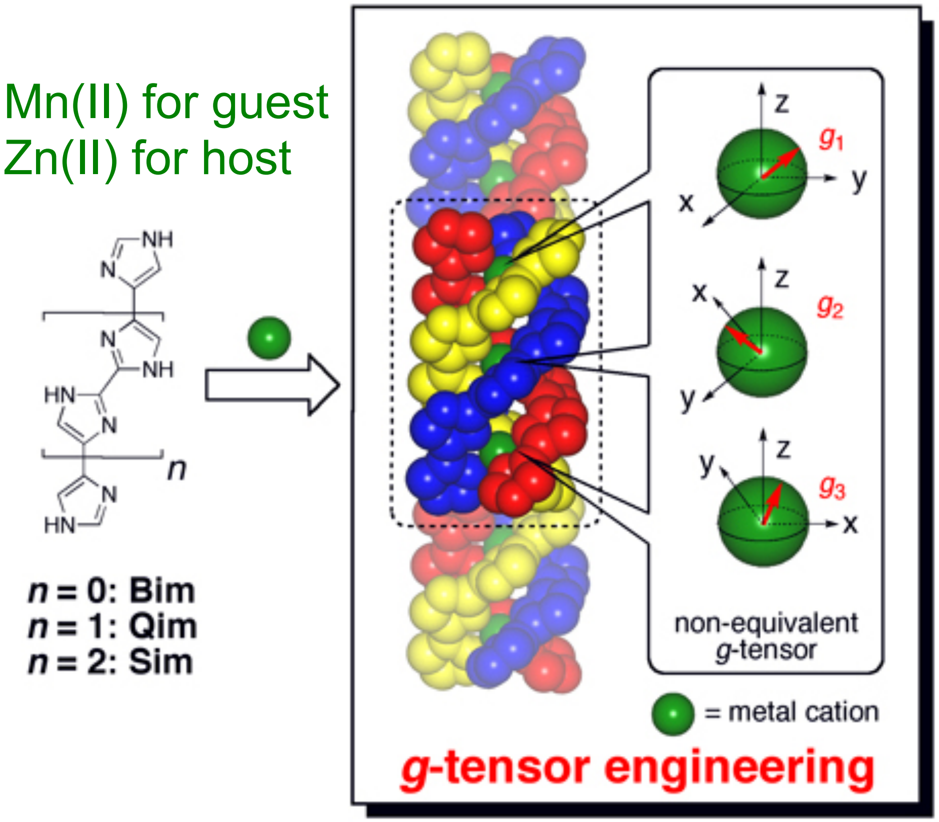


- Only 16 frequencies are required to build universal quantum circuit on (ABC)n regardless of n
- Less harmful control-induced decoherence
- Overhead is $O(n)$ and not exponentially hard
- Other quantum cellular automaton like architecture

Potentially Scalable Molecular Spin Quantum Computer

Supramolecular chemistry approach
Triple-stranded metallo-helicates
based on oligo(imidazole)s ligands

Mn(II) for guest
Zn(II) for host

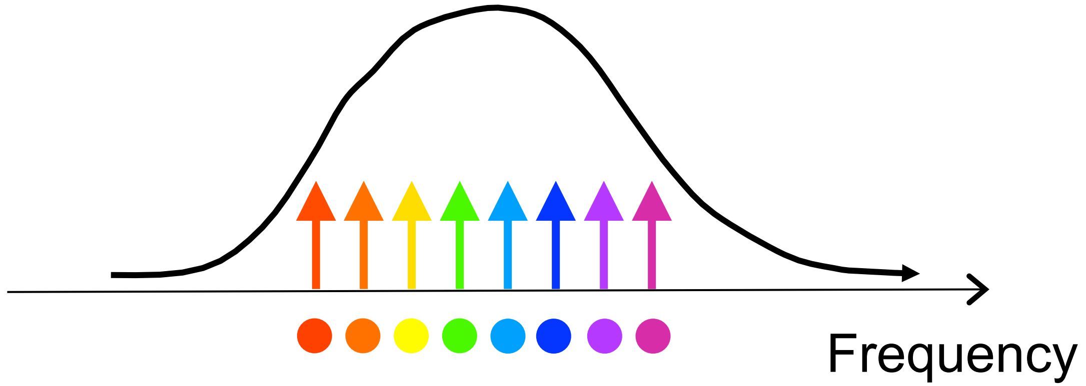


Y. Morita, Y. Yakiyama, *et. al.*

Possible realization with nuclear spins

ideal: (F, ^{1}H, P), (F, ^{1}H, ^{13}C)
realistic: (^{1}H, ^{1}H, ^{13}C), (^{1}H, ^{13}C, ^{13}C)

Chirp-free hyper-precision pulse anywhere in the resonator bandwidth



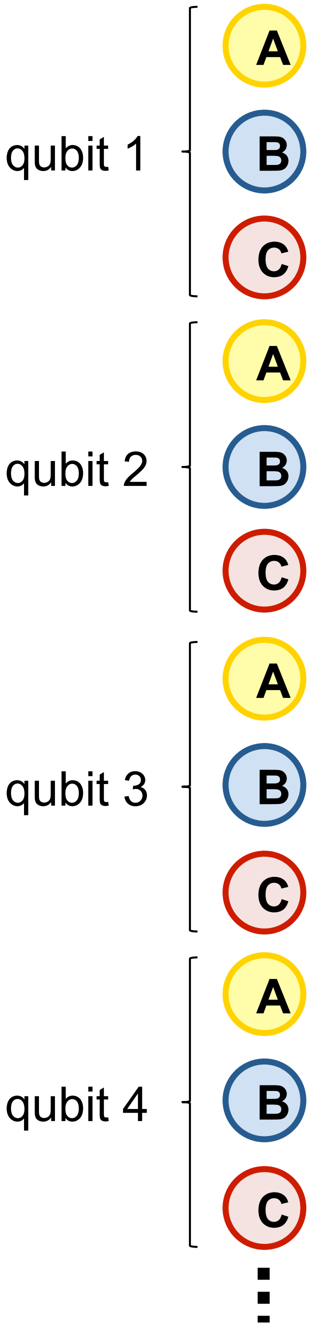
Homo-nuclear qubits (chemical shifts)

Electron spin qubits (g-tensor engineering)

16 frequencies for $(ABC)_n$ scalable qubits

Precision pulse irradiation with arbitrary detuning for quantum optical experiments

1D Lloyd Model



A: Header bit
B: Register bit
C: Memory bit

- Initialization
- Selective NOT$_{\text{edge-A}}$ (Only edge becomes 1, Header)
- 1qubit rotation
  - SWAP$_{A\Leftrightarrow B}$ SWAP$_{B\Leftrightarrow C}$ SWAP$_{C\Leftrightarrow A}$ (Moving Header into Data)
  - Controlled$_A$-SWAP$_{B\Leftrightarrow C}$
  - Controlled$_A$-Rotation$_B$
  - Controlled$_A$-SWAP$_{B\Leftrightarrow C}$
- CNOT
  - SWAP (Moving Header to Control qubit)
  - Controlled$_A$-SWAP$_{B\Leftrightarrow C}$
  - SWAP (Moving Header and Control qubit to Target qubit)
  - Controlled$_A$-Controlled$_B$-NOT$_C$
  - SWAP (Moving Control qubit to the original position)
- Selective Measurement$_{\text{edge-A}}$

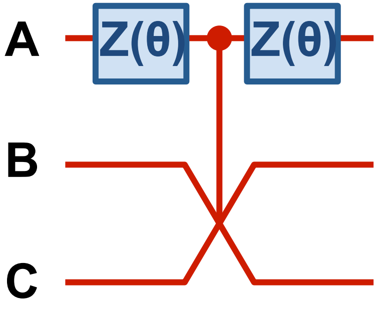
Global Control of 1D Lloyd Model

- SWAP$_{A\Leftrightarrow B}$ SWAP$_{B\Leftrightarrow C}$ SWAP$_{C\Leftrightarrow A}$

  Moving Header arround
- Controlled$_{A}$-SWAP$_{B\Leftrightarrow C}$
- Controlled$_{A}$-Rotation$_{B}$
- Controlled$_{A}$-Controlled$_{B}$-NOT$_{C}$

Data and Register with Header are quantum

Others are classical



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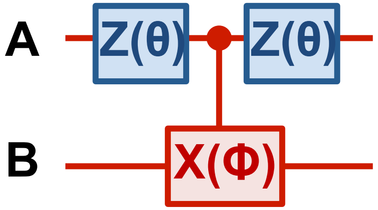
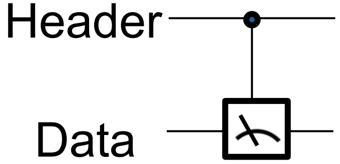


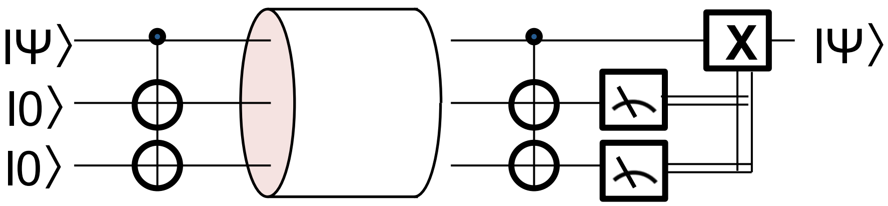
suffice

Fault-Tolerant QC

- Controlled$_{\text{Header}}$-Measurement
- Without Measurement
  - – QEC [Nielsen & Chuang QCQI]

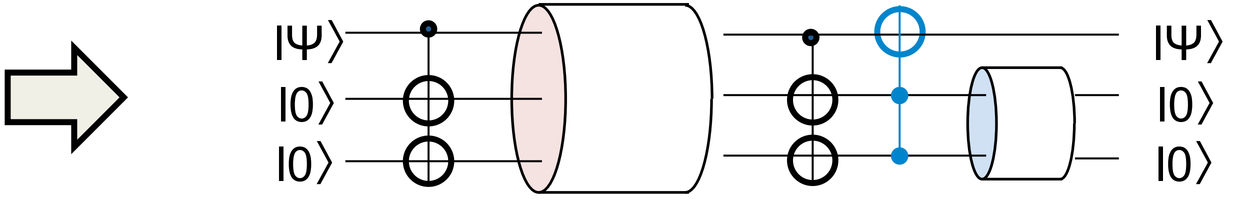
Measured iff Header is 1





Bit Flip Channel

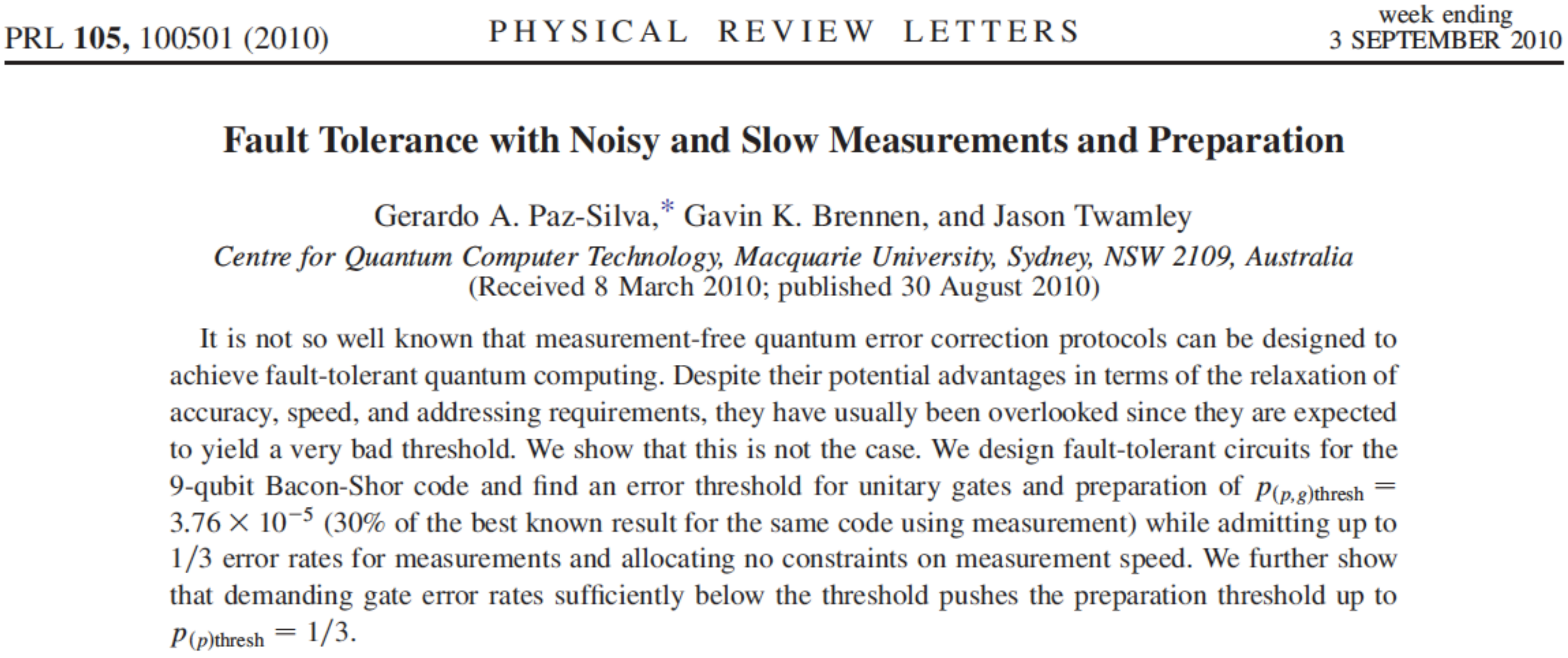
QEC w projective meas.
=Controlled operation
+Cooling



Bit Flip Channel

Cooling Channel

Fault-tolerant w/o measurement



PRL **105,** 100501 (2010) PHYSICAL REVIEW LETTERS week ending 3 SEPTEMBER 2010

Fault Tolerance with Noisy and Slow Measurements and Preparation

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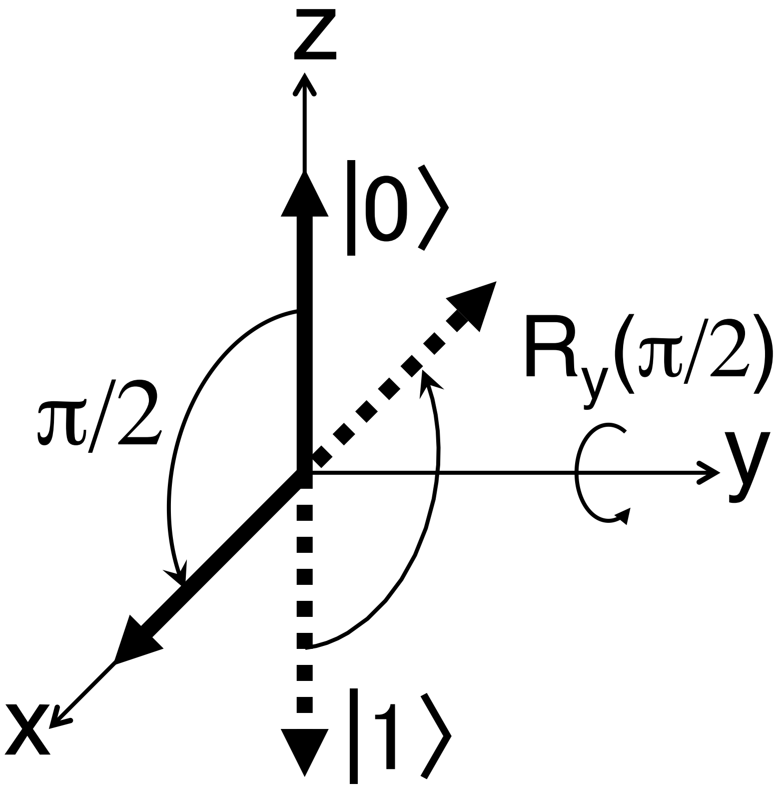
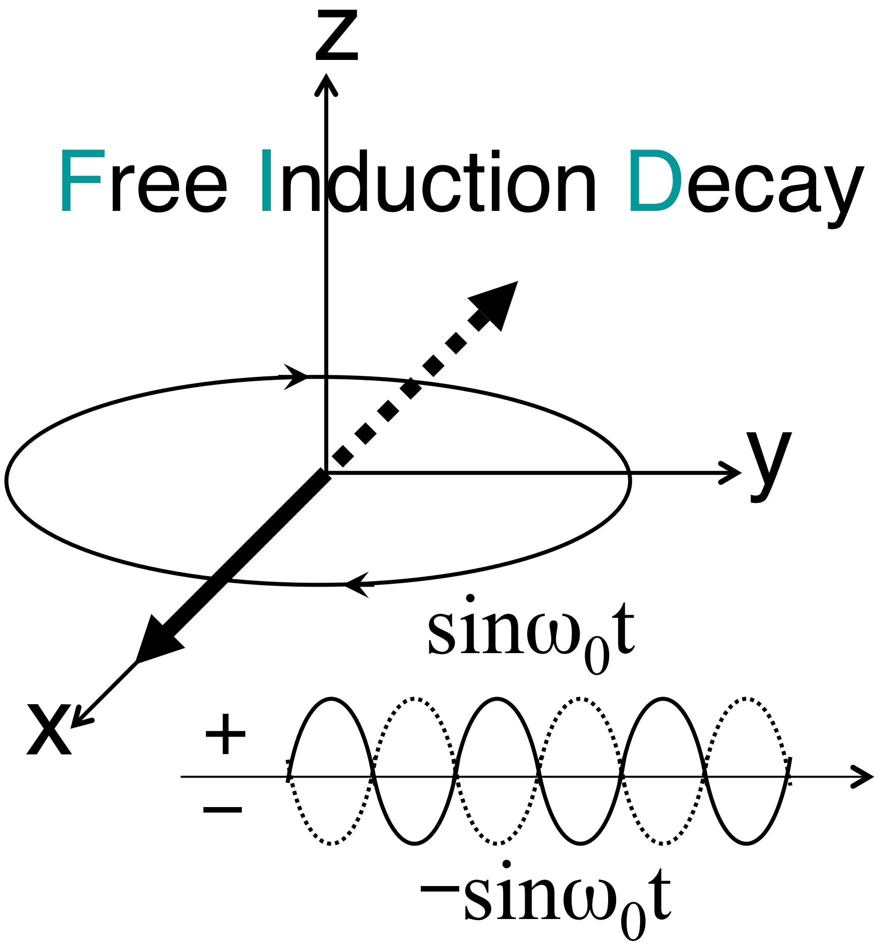
(Received 8 March 2010; published 30 August 2010)

It is not so well known that measurement-free quantum error correction protocols can be designed to achieve fault-tolerant quantum computing. Despite their potential advantages in terms of the relaxation of accuracy, speed, and addressing requirements, they have usually been overlooked since they are expected to yield a very bad threshold. We show that this is not the case. We design fault-tolerant circuits for the 9-qubit Bacon-Shor code and find an error threshold for unitary gates and preparation of $p_{(p,g)\mathrm{thresh}} = 3.76 \times 10^{-5}$ (30% of the best known result for the same code using measurement) while admitting up to 1/3 error rates for measurements and allocating no constraints on measurement speed. We further show that demanding gate error rates sufficiently below the threshold pushes the preparation threshold up to $p_{(p)\mathrm{thresh}} = 1/3$.

Spin Amplification

Readout of spin qubit





FID signal from single nuclear spin is too weak to detect

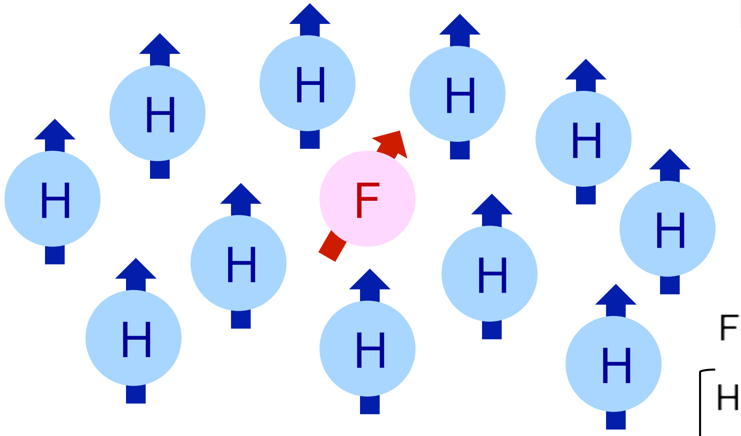
$10^6 \sim 10^{14}$ nuclear spins are required

Projective measurement is not available

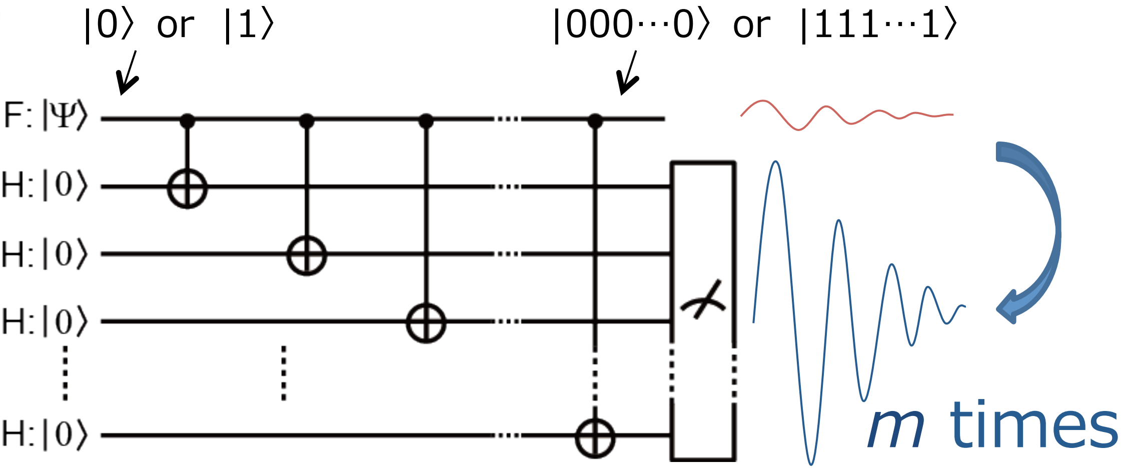
Spin Amplification by Copying

Copying arbitrary unknown state is prohibited by no-cloning theorem, but copying whether the state is |0> or |1> is not. A spin component can be amplified.

[D. DiVincenzo, Fortschr Phys. **48**, 771 ('00)]



To determine whether the state of F spin surrounded by m abundant H spins is |0⟩or |1⟩

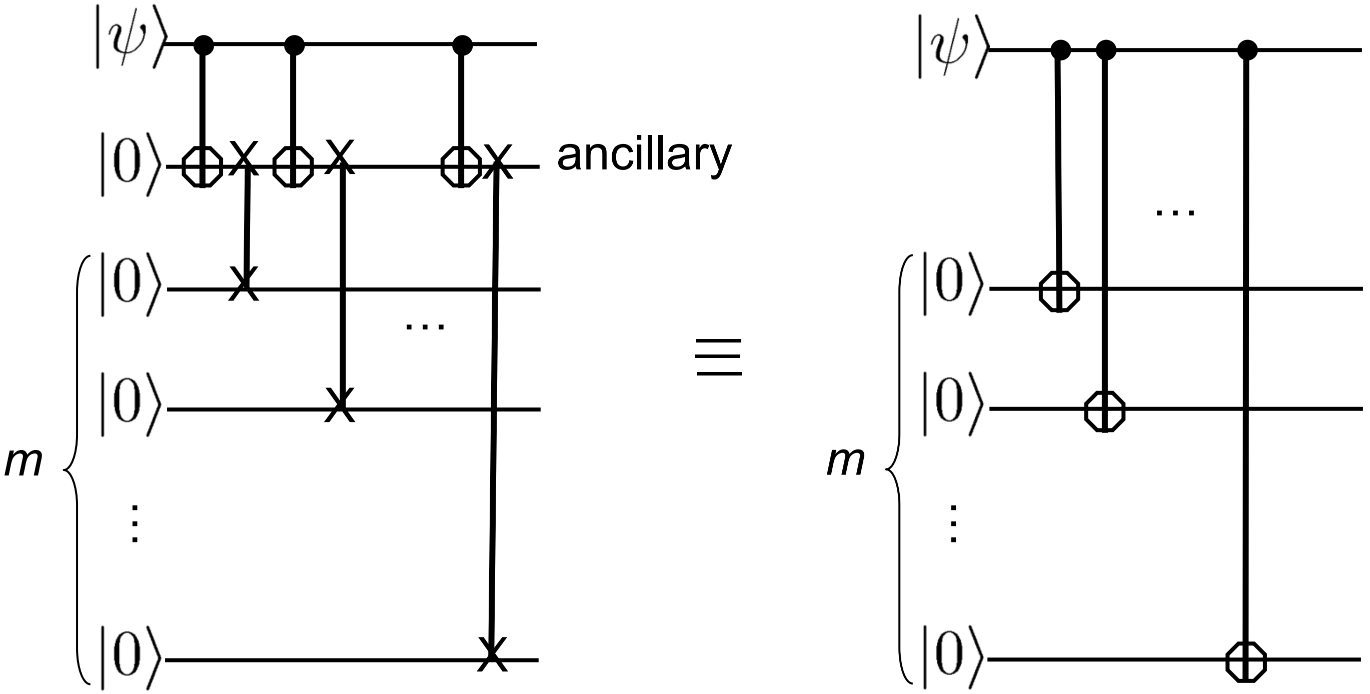


Minimum detectable number of spins (10^6 : induction, 10^2: MRFM) can be reduced by spin amplification

Spin Amplification by SWAPs

Input

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$$



Still difficult to build quantum circuits for large *m*,
say, *m*=100, 1000, …

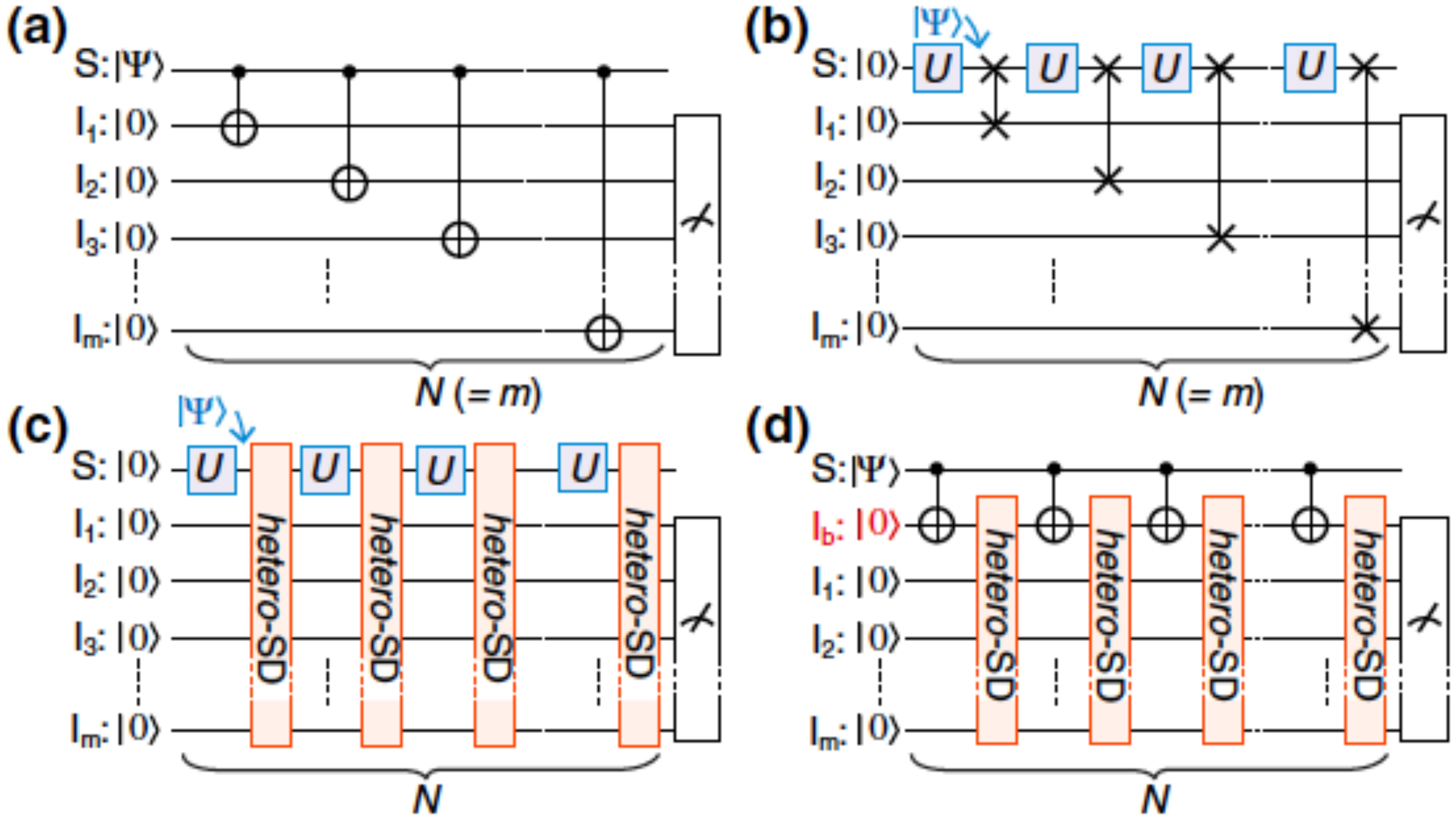
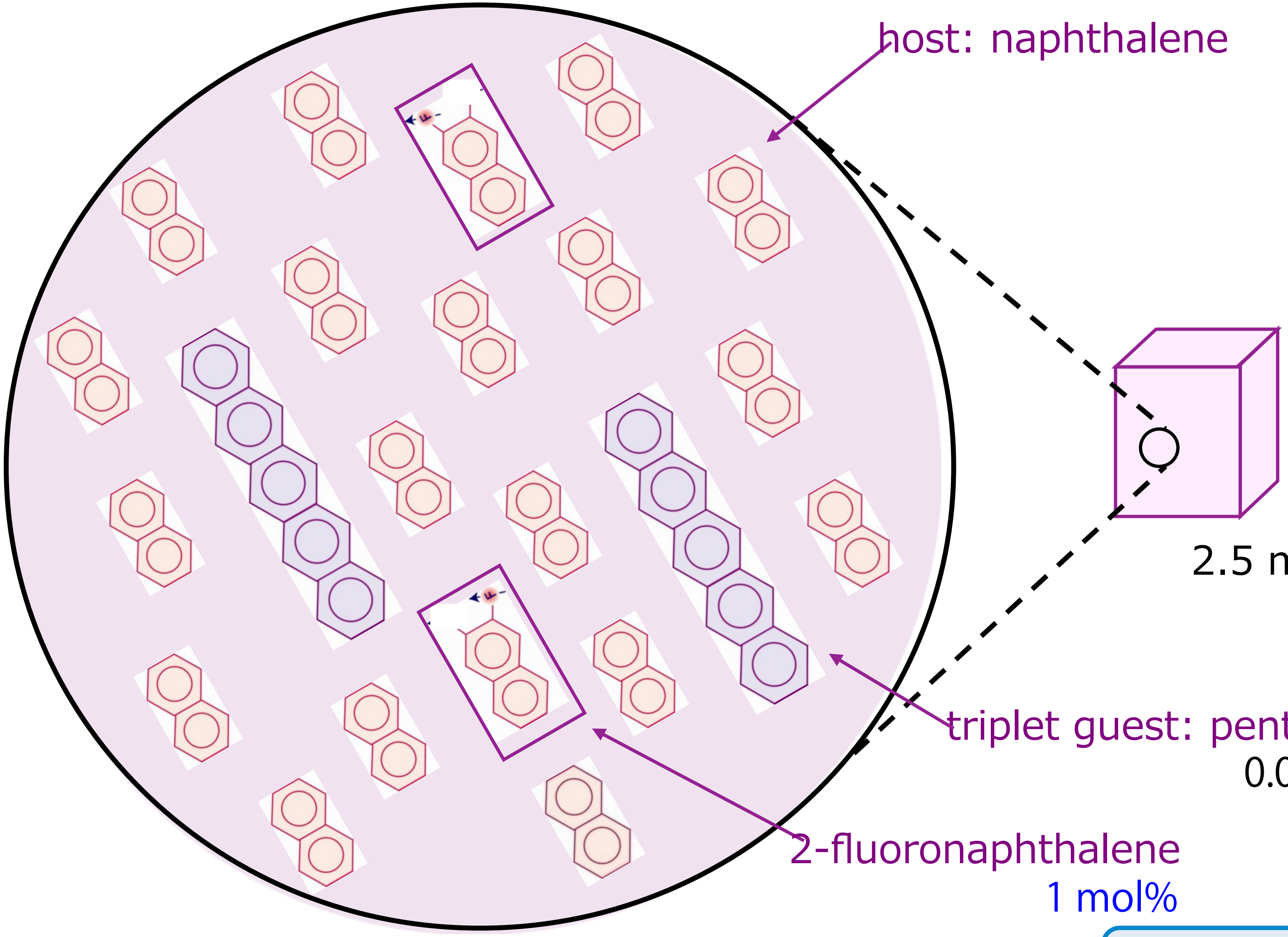


FIG. 1 (color online). (a) Spin amplification referred to by DiVincenzo [1]. (b) Spin amplification of the S spin response signal using selective SWAP gates and (c) that using the hetero-SD process. (d) Scalable version of (a). The I spins are initialized to $|0\rangle$ for simplicity, although they do not have to be in practice.

Sample system: doubly doped crystal



host: naphthalene

2.5 mg

triplet guest: pentacene
0.005 mol%

2-fluoronaphthalene
1 mol%

H : F =799 : 1

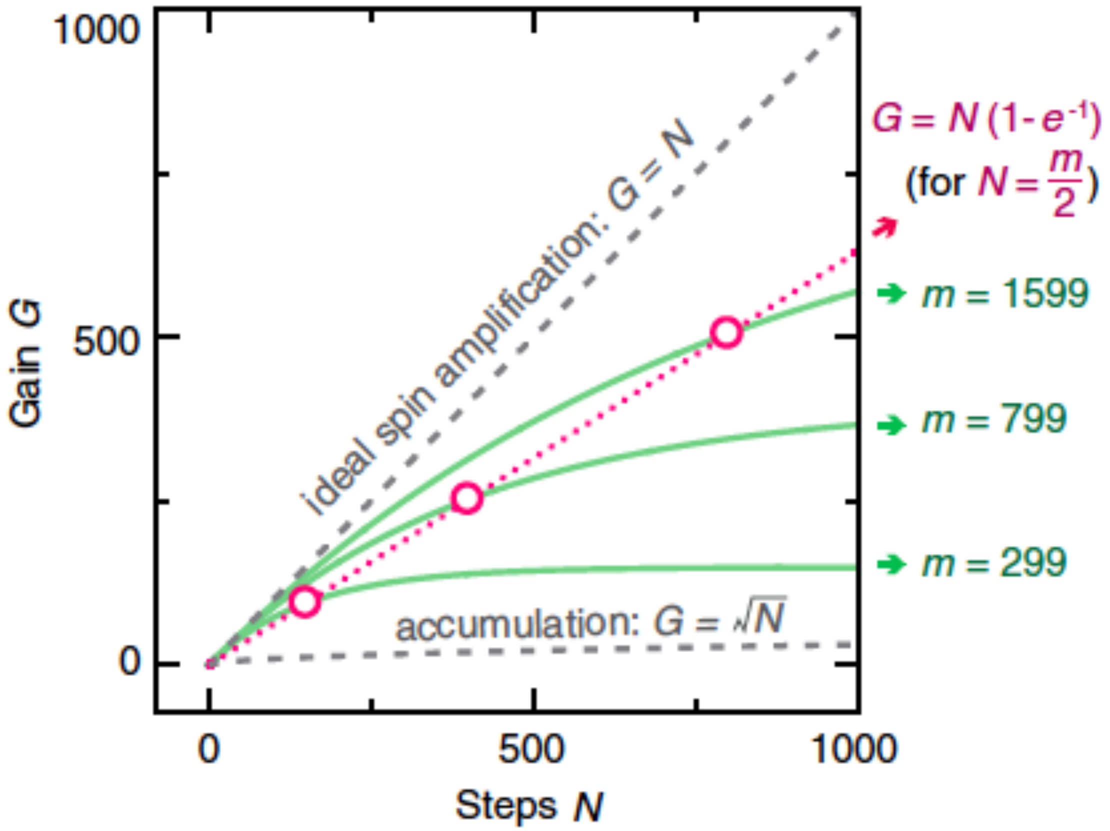


FIG. 2 (color online). The top dashed line shows the gain G of the SNR of ideal spin amplification [Figs. 1(a) and 1(b)] with respect to the number of SWAP gates N. The solid lines show the expected gain [Eq. (2)] of the proposed one [Fig. 1(c)] with respect to the number of the hetero-SD process gates N for different system sizes. The bottom dashed line shows the gain of the direct simple repetitive detection with respect to the number of repetitions N.

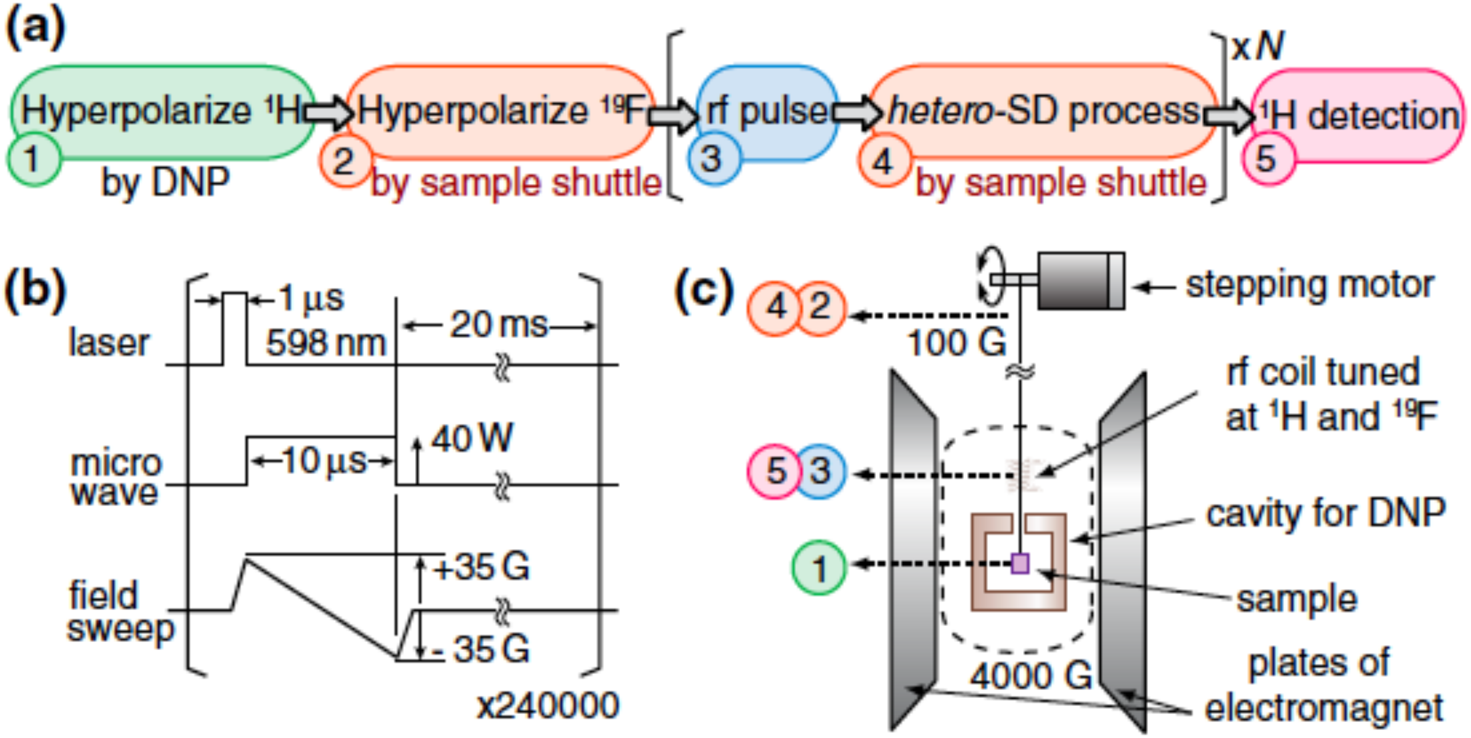


FIG. 3 (color online). (a) An experimental procedure of spin amplification using the hetero-SD process [15]. (b) A DNP sequence with integrated solid effect [16]. (c) A schematic diagram of an experimental setup where the sample position at each stage is indicated.

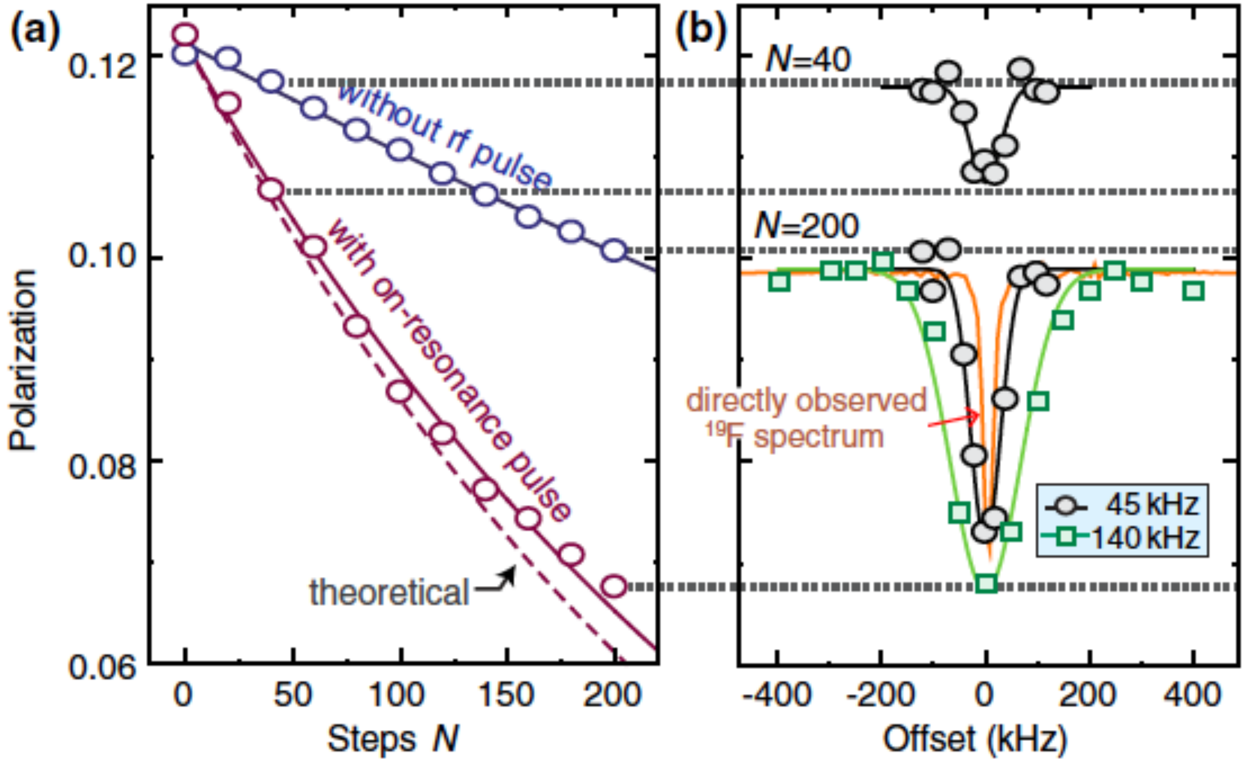
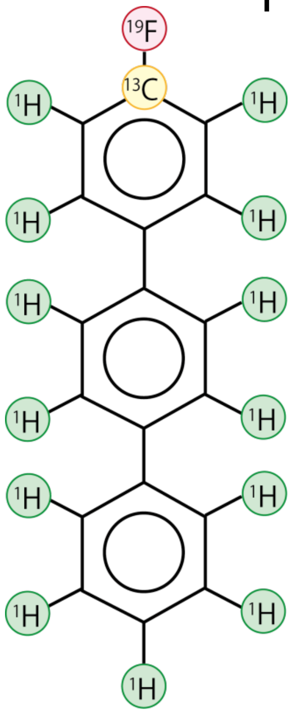


FIG. 4 (color online). (a) The behaviors of the ^{1}H spin polarization with respect to the number of steps N of spin amplification without rf pulse ($U = \boldsymbol{I}$) and with on-resonance π pulses ($U = \text{NOT}$). The dashed line is the theoretical decay. (b) The circles show the spin-amplified frequency response spectra obtained for $N = 40$ and 200. They were obtained with the rf pulse with a peak amplitude of 45 kHz (the pulse length is ~3 times as long as that of 140 kHz). The squares show the spin-amplified frequency response spectra obtained for $N = 200$ with the rf pulse with a peak amplitude of 140 kHz. Directly detected ^{19}F spectrum vertically magnified is also shown for comparison.

QND meas. with Spin Amplification

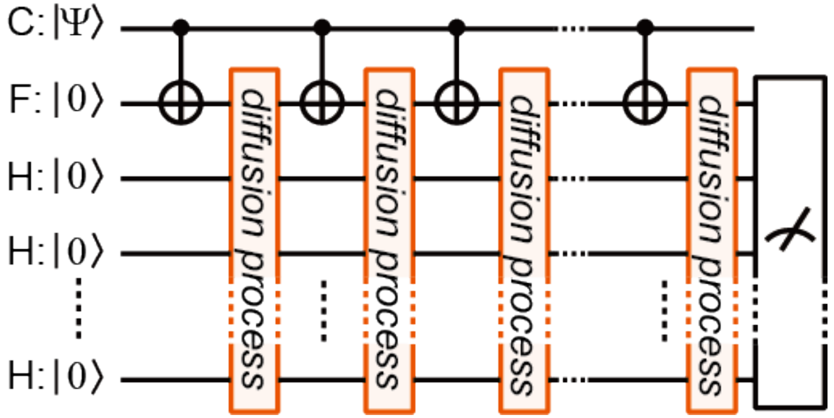
1-^{13}C, 1-Fluoro-*p*-terphenyl : *p*-terphenyl = 1: 20

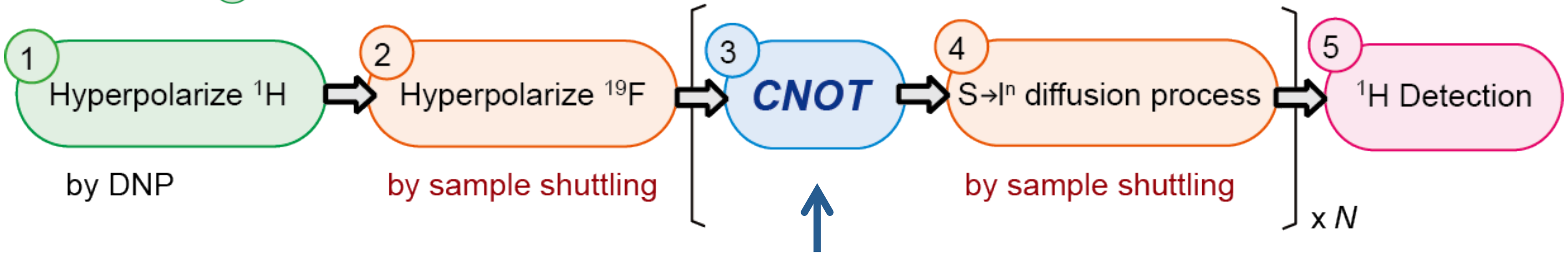
Polarization @RT > 10% [M. Negoro, *et al.*, J. Chem. Phys. (2011)]



^{1}H : ^{19}F : ^{13}C ∼ 300 : 1 : 1

max GAIN = 150





1. Hyperpolarize ^{1}H
   by DNP
2. Hyperpolarize ^{19}F
   by sample shuttling
3. **CNOT**
4. S→I^{n} diffusion process
   by sample shuttling
5. ^{1}H Detection

x *N*

Only this part is modified

Noiseless Quantum Amplification

• Photon (Boson)	• Spin
• Degenerate Parametric Amplifier – Amplify a_1 – De-amplify a_2	• Spin Squeezing Amplifier – Amplify S_x – De-amplify S_y
• Number Amplifier – Amplify N – Erase ϕ	• Spin Amplifier – Amplify S_z – Erase S_x and S_y
• Laser (isotropic & noisy)	
• Non-degenerate Paramp – Amplify both a_1 and a_2 – Inevitable quantum noise	• Isotropic Spin Amplifier – Amplify S_x, S_y and S_z – Inevitable quantum noise

Thank you for your attention