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NMR Quantum Information Processing: Successes and Challenges

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Washington, 24th of April 2009

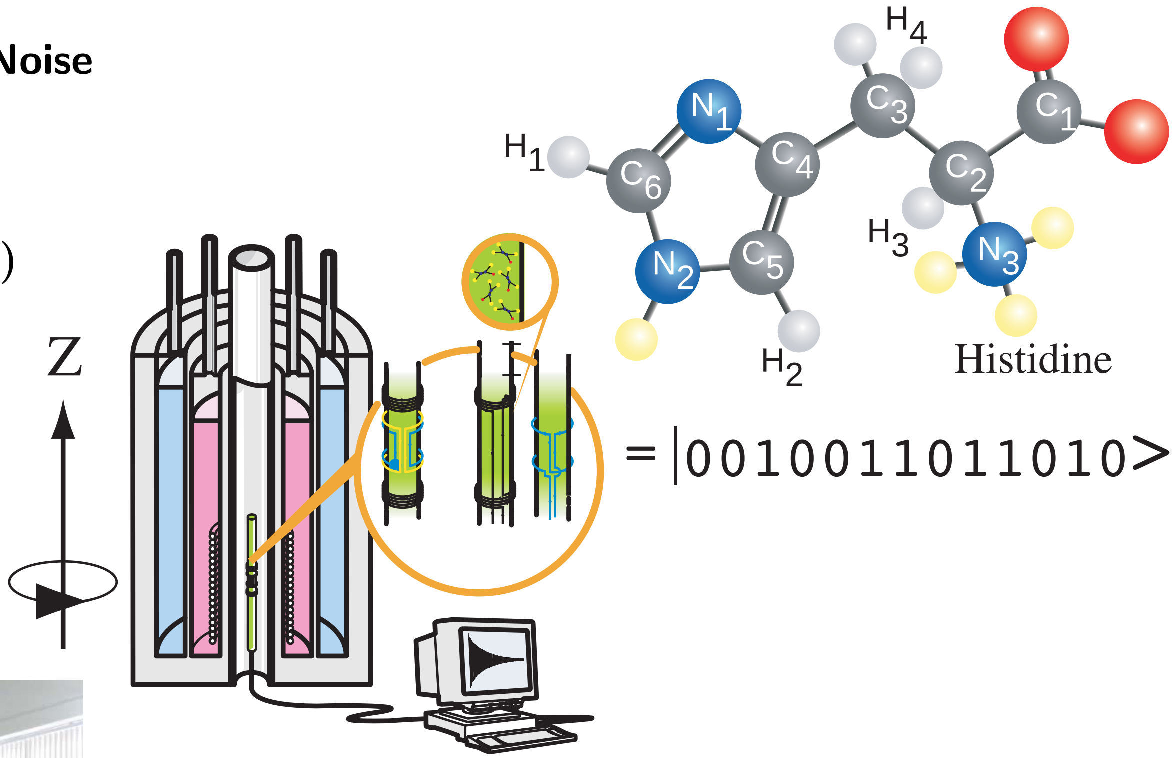
Liquid state NMR

Cory & Havel PNAS, 64, 1634, 1997

Gershenfeld & Chuang, Science 275, 350, 1997

Qubits/Control/Measurement/Noise

- Larmor frequency:
  $\omega_L = \mu_p B_0 =\sim$ 500 MHz
- Single bit gate: $H = \vec{\mu} \cdot \vec{B}$
  $\sim \omega_L Z^1 + \mu(B_x X + B_y Y)$
  $\sim$ 1/kHz $\sim$ ms
- Two bit gate $\sim$10 ms: $\vec{J}^1 \cdot \vec{J}^2$
  $H_{int} \sim J_{12} Z^1 Z^2$
- $T_2 \sim$ 1s ; $T_1 \sim 10s$



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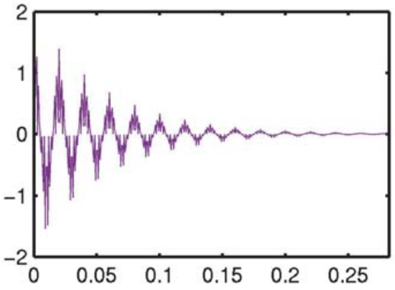
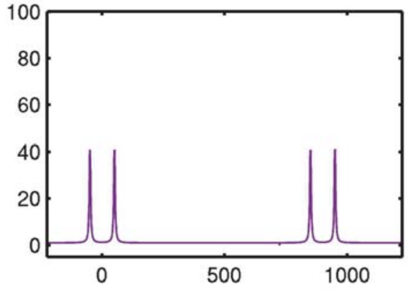
Bruker 700





Initial state in Liquid state NMR

We have highly mixed state at room temperature.

- **Making a “pseudo pure” state** **(Cory et al. 1996, Gershenfeld et al. 1997)**

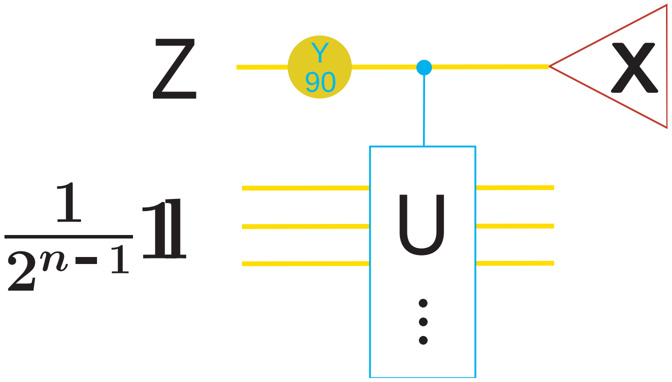
$$\rho = \frac{1}{Z}e^{-\beta H} \approx \frac{1}{Z}(\mathbb{1}-\beta H+\dots) \rightarrow \frac{1}{Z}\left(\mathbb{1}-\frac{\beta\omega n}{2^n}|\Psi\rangle\langle\Psi|\right) \; (\textit{not scalable})$$

BUT: Schulman and Vazirani (STOC, 322, 1999): Algorithmic cooling (i.e. concentrate polarization of the qubits) is scalable.

- **The power of one bit of quantum information**

E. Knill& R.L. PRL81, 5672, 1998

-Interpretation of tomography and spectroscopy as dual forms of quantum computation, Miquel, C. et al., Nature 418, 59-62, 2002.
-Characterization of complex quantum dynamics with a scalable NMR information processor Ryan, C, PRL 95, 250502, 2005.
-Estimating Jones polynomials is a complete problem for one clean qubit Shor, P. et a., QIC 8, 681, 2008.
-. . .



Accuracy threshold theorem

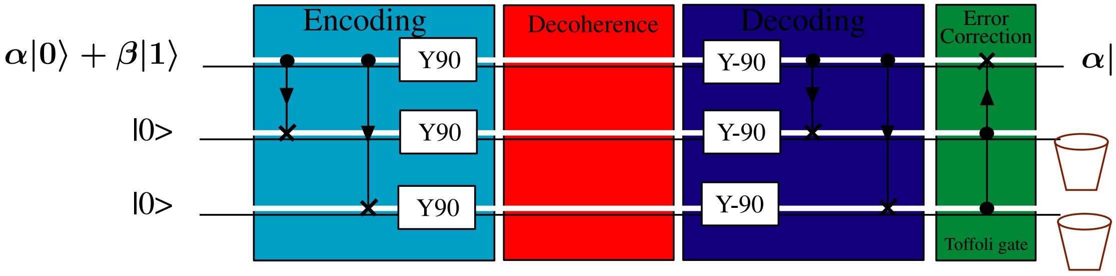
- Quantum error correction has been one the major achievement in QIP. Assumptions of the theorem:

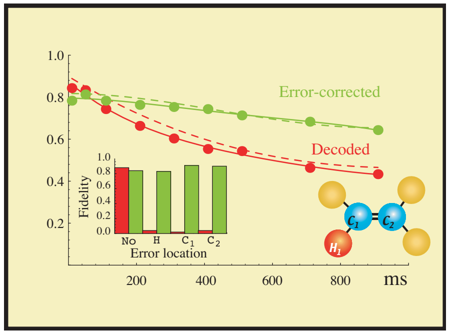
- **Good quantum control**
- **Parallel operations**
- **Ability to extract entropy**
- **Knowledge of the noise**
  - No lost of qubits
  - Independent or quasi independent errors
  - Depolarising model
  - Memory and gate errors
  - . . .

Quantum Control

Implementation of quantum error correction:

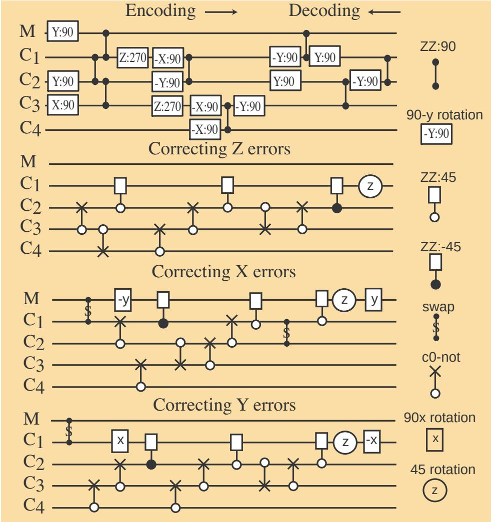
- **3 qubits or phase quantum error correcting code**



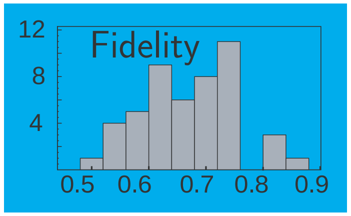


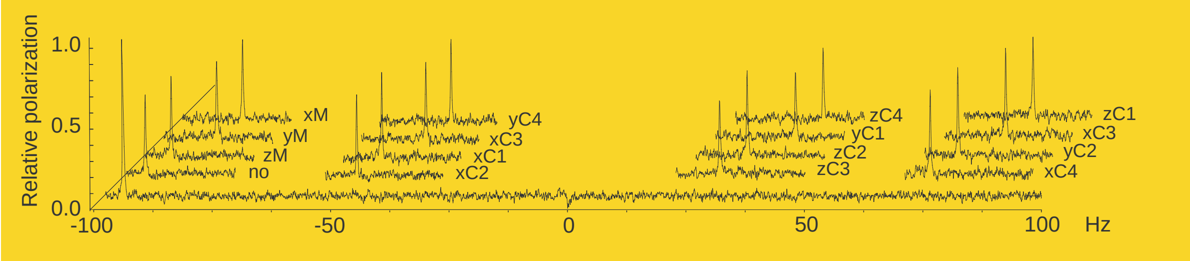
Cory et al., PRL 81, 2152, 1998

- **5 qubits quantum error correcting code**



Implementation of the 5 bit code with the stabilizer $Z^2Y^3Y^4X^5$, $Z^1Y^2Y^3X^4$, $Y^2Z^3Z^4Z^5$ and $X^1Z^2X^3Z^4$, including decoding and error correction for a basis of 1 qubit errors.



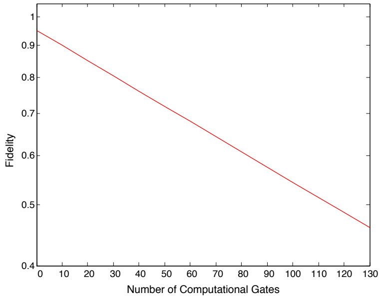


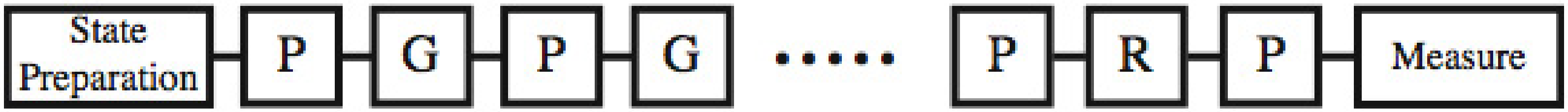
Knill et al. PRL 86, 5811 (2001)

Benchmarking

Estimate the accuracy of gates such that:

- **Device indepedent**
- **Independent of state prep and measurement**
- **Characterised by one parameter (strength of the depolarised noise)**





G gates - Clifford group generators, P gates - Pauli gates, R gate - recovery operation

	liquid-state NMR	ion traps	superconducting qubits
single-qubit	$1.3 \pm 0.1 \times 10^{-4}$ [1]	$4.82 \pm 0.02 \times 10^{-3}$ [2]	$1.1 \pm 0.3 \times 10^{-2}$ [3]
multi-qubit	$4.7 \pm 0.3 \times 10^{-3}$ [1]	$99.3\%^{*}$ [4]	$55\%^{*}$ [5]

[1] C.A.Ryan, M. Laforest and R. Laflamme. Randomized benchmarking of single- and multi-qubit control in liquid-state NMR quantum information processing. New Journal of Physics 11: 013034 (2009).
[2] E. Knill et al. Randomized benchmarking of quantum gates. Physical Review A 77: 012307 (2008).
[3] J.M. Chow et al. Randomized benchmarking and process tomography for gate errors in a solid-state qubit. arXiv:0811.4387 (2008).
[4] J. Benhelm, G. Kirchmair, C.F. Roos and R. Blatt. Towards fault-tolerant quantum computing with trapped ions. Nature Physics 4: 463 (2008).
[5] S. Filipp et al. Two-Qubit State Tomography using a Joint Dispersive Read-Out. arXiv:0812.2485 (2008).