Beating the thermal limit of qubit initialization with a Bayesian “Maxwell’s Demon”

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Motivation

Fidelity requirements of Surface Code

• single- and two qubit gate fidelities: $\geq 99\%$
• state preparation and measurement (SPAM) fidelity: $\geq 99\%$

• systems based on energy-selective tunnelling: ultimately limited by temperature
• readout fidelity: can be improved by QND measurement $^2$
• here: overcome temperature limit of initialization
  • for high-temperature operation
  • or higher fidelity at lower temperature

$^1$A. G. Fowler, M. Mariantoni, J. M. Martinis, and A. N. Cleland, Phys. Rev. A 86, 032324 (2012)
$^2$J. Yoneda et al., Nat. Commun. 11, 1144 (2020)
$^3$J. M. Elzerman et al., Nature 430, 431–435 (2004)
Basic idea

Maxwell’s Demon
• thought experiment: use a “demon” to separate hot and cold gas particles

„qubit initialization“ demon
• load cold electrons into the QD and leave warm electrons in the reservoir
• beat theoretical limit for qubit initialization fidelity

1 J. M. Elzerman et al., Nature 430, 431–435 (2004)
Setup

Device: donor QD

- $^{31}$P donor in enriched $^{28}$Si
- MW antenna for ESR and NMR
- SET as reservoir and charge sensor (50kHz)
- control setup via FPGA at 100MHz
Qubit initialization

Spin-dependent tunneling

- Probability for loading $|\downarrow\rangle$ or $|\uparrow\rangle$ is given by Fermi distribution:

$$f(E) = \left(1 + \exp\left(\frac{E - E_F}{k_B T_e}\right)\right)^{-1}$$

- If $E_z >> k_BT \rightarrow$ mostly $|\downarrow\rangle$ is loaded
- Probability to load $|\downarrow\rangle$ is limited by finite $T$

$$P(\downarrow) = f(E_\downarrow)$$
Bayesian Maxwell’s Demon

Negative-outcome measurement

• if $|\uparrow\rangle$ is loaded, electron tunnels out fast since $\Gamma_{\uparrow,\text{out}} \gg \Gamma_{\downarrow,\text{out}}$

• absence of a tunneling event provides information on spin state without destroying the state

$^1$D. Keith et al., New J. Phys. 21 063011 (2019)
Bayesian Maxwell’s Demon

Discrete Bayesian model

- integration time $T_S = 10\mu s$
- N number of measurements
- measurement outcome
  - $B$ = tunneling detected
  - $\neg B$ = no tunneling detected
- prior probablility $P(\downarrow) = f(E_\downarrow)$
- probability to not observe a tunneling event:
  $$\mathcal{L}(\neg B_1 | \uparrow) = e^{-T_s \Gamma_{\uparrow, out}}$$
  $$\mathcal{L}(\neg B_1 | \downarrow) = e^{-T_s \Gamma_{\downarrow, out}}$$

- after N measurements with outcome $\neg B$ posterior probability is

$$P(\downarrow | \neg B^N) = \frac{\mathcal{L}(\neg B^N | \downarrow) P(\downarrow)}{\mathcal{L}(\neg B^N | \downarrow) P(\downarrow) + \mathcal{L}(\neg B^N | \uparrow) P(\uparrow)}$$

$$= \frac{1}{1 + \frac{\mathcal{L}(\neg B^N | \uparrow) P(\uparrow)}{\mathcal{L}(\neg B^N | \downarrow) P(\downarrow)}}$$

$$= \left(1 + \frac{1 - P(\downarrow)}{P(\downarrow)} e^{-NT_s (\Gamma_{\uparrow, out} - \Gamma_{\downarrow, out})}\right)^{-1},$$

\rightarrow goes towards 1 for large N
Bayesian Maxwell’s Demon

(a) Empty and Reload

Cool ~20ms

(b) i) ii) iii) iv)
Total fidelity $F = F_I F_C F_R$

- initialization fidelity: $F_I$
- NMR control\(^1\) fidelity: $F_C \sim 99.5\%$
- QND readout\(^2\) fidelity: $F_R \sim 99.99\%$
- additionally: missed blips on detector $P_M$

Fidelity increase:

$F_I(0) \sim 78\%-80\%$

$F_I = 98.9\%$

\(^1\)S. Freer et al., Quantum Science and Technology 2, 015009 (2017)

\(^2\)J. J. Pla et al., Nature 496, 334 (2013)
Fidelity robustness

- detune initialization level $\mu_D$
- initialization with feedback shows plateau of width $\sim E_Z/2$

Fidelity robustness against detuning increases
"Effective" temperature

\[
\Gamma_{\uparrow,\text{in}}(T_{\text{eff}}) = \frac{2\pi}{\hbar} \left| \langle \uparrow | H' | 0 \rangle \right|^2 n(E_{\uparrow}) f(E_{\uparrow})
\]

\[
\Gamma_{\downarrow,\text{in}}(T_{\text{eff}}) = \frac{2\pi}{\hbar} \left| \langle \downarrow | H' | 0 \rangle \right|^2 n(E_{\downarrow}) f(E_{\downarrow})
\]

- fails to reproduce fidelity \( \mathcal{F}_{1}^{\text{NF}} = \frac{\Gamma_{\downarrow,\text{in}}}{\Gamma_{\downarrow,\text{in}} + \Gamma_{\uparrow,\text{in}}} \)
- phenomenological parameter

\[
\chi = \frac{n(E_{\uparrow}) \left| \langle \uparrow | H' | 0 \rangle \right|^2}{n(E_{\downarrow}) \left| \langle \downarrow | H' | 0 \rangle \right|^2} \approx 0.388
\]

\[
\mathcal{F}_{1}^{\text{NF}} = \frac{1}{1 + R_{\text{in}}} = \frac{1}{1 + \chi \frac{f(E_{\uparrow})}{f(E_{\downarrow})}}
\]
Limitations

Limiting factors of the detector\textsuperscript{1}

- sample rate: 100MS/s
- signal-to-noise: $>>1$
- LP filter: 50kHz

- 99.9\% initialization fidelity possible with
  ~300kHz bandwidth
  or ~880Hz electron tunneling rate

\textsuperscript{1}D. Keith \textit{et al.}, New J. Phys. 21 063011 (2019)