Domain Walls in 1D: Simple Experiments to Answer Important Questions

Nick Chancellor

London Centre for Nanotechnology, University College London

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Collaborators:

Philip Crowley

Tanja Duric

Walter Vinci

Andrew G. Green

Paul Warburton

Mohammad Amin

Gabriel Aeppli

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LOCKHEED MARTIN

Presentation Structure

1. Order-by-disorder effects on a forced domain wall
   1.1 "Particle In a Box" experiment
   1.2 Cause of the U-shape
   1.3 Using this to measure control errors
2. Domain wall tunneling
   2.1 Tunneling experiment
   2.2 Other uses of protocol

Part 1.1: "Particle In a Box" experiment

Relatively simple spin chain Hamiltonian:

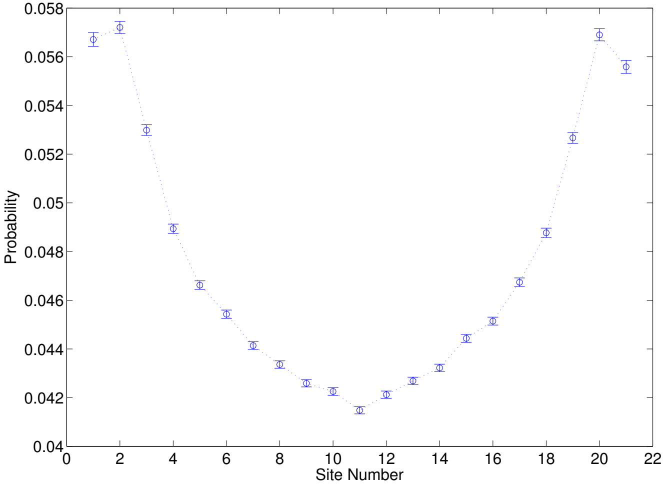
$$H(t) = B(t)(\sum_{i=1}^{N-1} -\sigma_i^z \sigma_{i+1}^z + 2\,(\sigma_1^z - \sigma_N^z)) - A(t)\sum_{i=1}^{N} \sigma_i^x$$

low energy sector for $A \ll B$ has exactly one domain wall

Note, experiments have been done before with this Hamiltonian:

Johnson, M. W. et. al. Quantum annealing with manufactured spins. *Nature* **473**, 194-198 (12 May 2011).

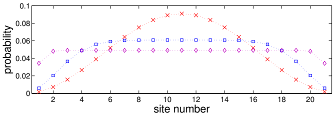
An unexpected result! U shaped domain wall distribution



?!

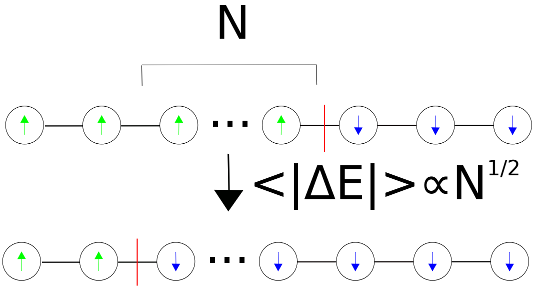
What could cause this? Usual suspects

1. Effect from transverse field -No!
   - We expect the opposite shape from transverse field



2. Annihilation -No!
   - Can lead to a U-shape, but erased by diffusion
   - Calculations and simulations predict equilibrium even for fastest anneal
   - U-shape seen even for long annealing time
3. Control errors -How?
   - Gauge and spacial averaging means that mean error will be the same everywhere on chain.
   - Gauge averaging will make errors (approximately) uncorrelated.
   - Can uncorrelated zero-mean errors do anything interesting?

Ising domain wall subject to uncorrelated random fields



- Typical energy difference between states depends on number of spins which are different
- Pair of states with domain wall further away tends to have bigger energy difference

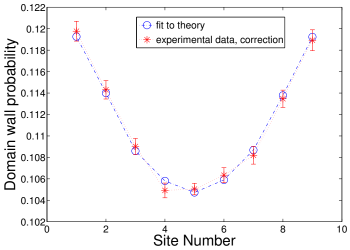
Domain wall energies are correlated even if fields are not!

These correlations lead to a U-shape

- Mathematically: Taylor expand domain wall probability $P_n = \overline{Z^{-1} e^{-\beta E_n}} = \overline{\left[1 + \sum_{m \neq n} e^{-\beta (E_m - E_n)}\right]^{-1}}$ in β to second order.
- Intuitively:
  - Domain walls on nearby couplers tend to have similar energy
  - Couplers on the end have fewer nighbours $\rightarrow$ fewer domain wall locations with similar energy
  - $\therefore Z = \sum_n \exp(-\beta E_n)$ tends to be smaller in cases where the domain wall has a high probability of being near the end

Measuring control errors with U-shape

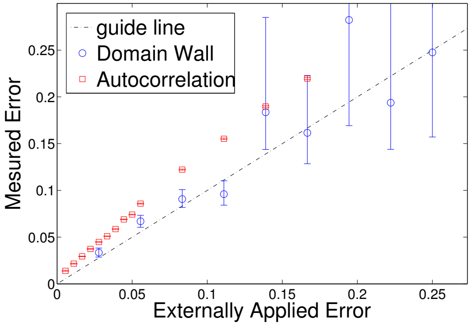
- For a chain of N spins, $N-1$ single domain wall states: Boltzmann distributions constructed exactly $\rightarrow$ sample with noise of various strengths $\rightarrow$ fit experiment to sampled



- Coupler control errors don't cause $\{E\}$ to be correlated $\rightarrow$ no effect on U
- Upper frequency limit related to equilibration timescale of the system and not to the annealing time

How does this compare with other ways of measuring?

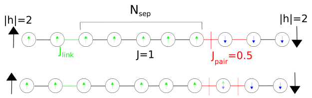
- Single qubit autocorrelation gives larger measurement of control error
- Also measures artificially introduced error more strongly



- Why the difference? one possibility is different freeze times

Part II: Domain wall tunneling

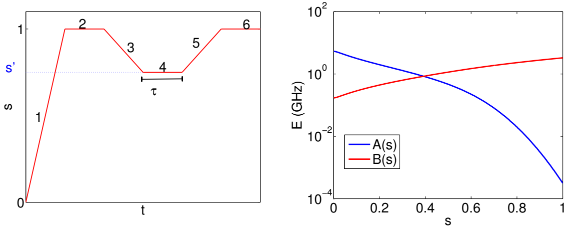
- Experiments which I will be performing over the summer at D-Wave headquarters in Burnaby B.C.
- Pattern Hamiltonian from part I with weak links to control domain wall resonances (more details later)



- More sophisticated annealing protocol allows initial state to be programmed
  - Extension of techniques used in Lanting, T. et. al. Entanglement in a Quantum Annealing Processor Phys. Rev. X 4 021041 (2014)

Our experiment vs. typical operation

- Typical annealing run: h_i and J_{ij} programmed at $s = 0 \rightarrow$ annealed linearly (in s) to $s = 1$ $\rightarrow$final state read out
- Our protocol:
  1. Program strong h_i and no J_{ij} to set initial state, anneal $s = 0 \rightarrow 1$
  2. At $s = 1$ reprogram h_i and J_{ij} to target Hamiltonian
  3. Anneal back to $0 < s' < 1$
  4. (optional) Wait for time τ
  5. Forward to $s = 1$
  6. Measure



Why would anyone want to do this?

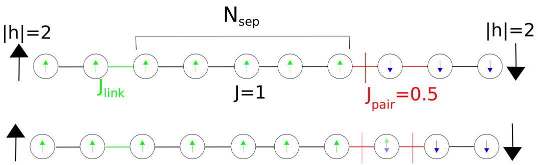
Current project:

- Preparing in an excited state allows for simple tunneling experiments
- Probe “freezing” transition
- Directly access information about control error earlier in anneal

Future projects:

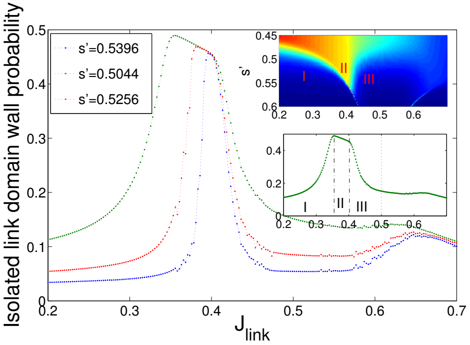
- Local search can be integrated with classical solvers in ways global search cannot
- Simulate diffusion of topological defects

Domain wall tunneling with controlled resonance



- Place forced domain wall on pair of weak links
- Another weak link N_{sep} qubits away
- Infinitesimal transverse field causes qubit next to weak link to hybridize and reduce energy
- Pair and single link DW positions come into resonance at a value of s which depends on J_{link}

Open quantum system simulations predict 3 regimes

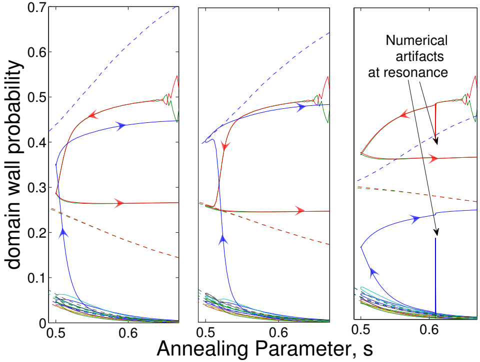


I Resonance limited: link and pair never get close enough to resonance for domain wall to tunnel

II Equilibration: resonance achieved at moderate transverse field; domain wall probabilities determined by detailed balance

III Freezing limited: resonance achieved at a point when transverse field too weak to facilitate tunneling

Are these explanations correct?



- Red and Green lines are weak link pair, Blue line is isolated link
- Arrows indicate time direction
- Dashed lines are thermal equilibrium

References

T. Lanting et. al. Entanglement in a Quantum Annealing Processor Phys. Rev. X 4 021041 doi: 10.1103/PhysRevX.4.021041 (2014)

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I Hen et. al.Probing for quantum speedup in spin glass problems with planted solutions arXiv:1502.01663 (2015)