Runback experiments on the D-Wave device

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LOCKHEED MARTIN

Summary

- Experiments which I will be performing over the summer at D-Wave headquarters in Burnaby B.C.
- User defined initial state subjected to Hamiltonian with transverse field
- Extension of techniques used in [1]*
  - In many ways our experiments are simpler (all qubits on the same annealing schedule).
  - Our experiment probes tunneling rather than entanglement
- May also provide a novel way to use software solvers alongside RF-SQUID hardware in hybrid calculation→ Related to Durham project goals

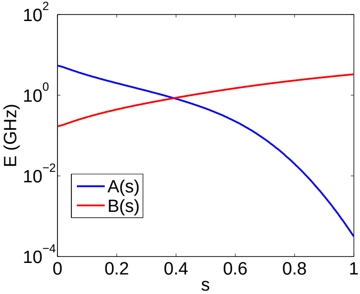
[0]*Lanting, T. et. al. Entanglement in a Quantum Annealing Processor Phys. Rev. X 4 021041 (2014)

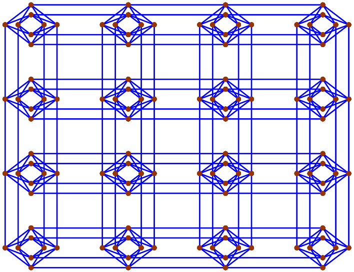
One slide Introduction to Hardware

- RF-SQUID Circuitry designed for Adiabatic Quantum Optimization (AQO), operates at $\sim 20\,mK$
- Maps to transverse field Ising model with hundreds of qubits on "chimera" graph, χ (h_i and J_{ij} set by user)

$$H(s) = A(s)\sum_i \sigma_i^x + B(s)\,(-\sum_i h_i\,\sigma_i^z - \sum_{ij\in\chi} J_{ij}\,\sigma_i^z\,\sigma_j^z)$$

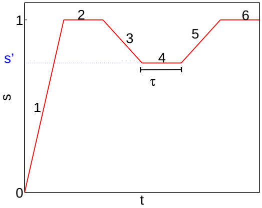
- A and B are controlled by the annealing parameter, s





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?

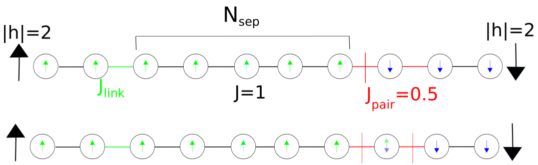
Current project:

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

Future projects:

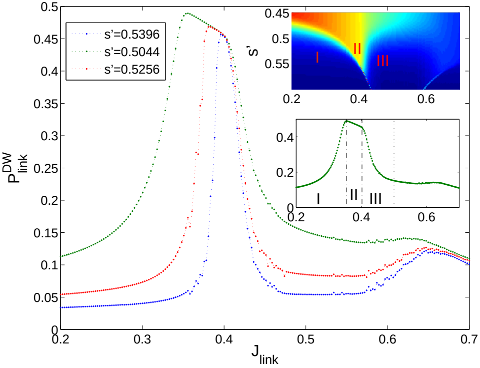
- Simulate diffusion of topological defects
- Local search can be integrated with classical solvers in ways global search cannot

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

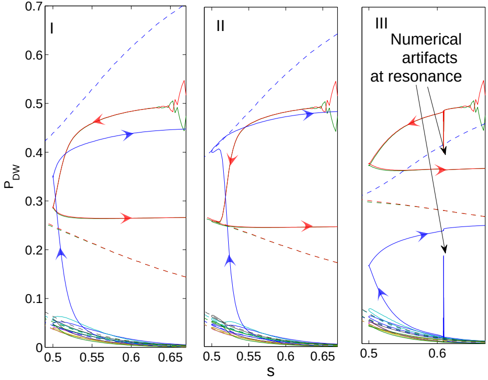


I Resonance limited: link and pair never get close enough to resonance for domain wall to tunnel

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

Could this protocol be useful computationally?

Standard Quantum Annealing Algorithm (QAA) is a global search

- Some ground states hard to find by QAA but easy to find in software (eg. chains)
- Approximate solutions from other methods cannot be used to help

This protocol is a local search

- Quantum fluctuations search state space around initial state
- Initial state can be solution found by software solver
- If software solver also takes initial states (eg. parallel tempering), can iterate back and fourth many times $\rightarrow$benefits of both but avoid pitfalls
- Disadvantage of relying on bath induced tunneling rather than adiabatic theorem

Thank you for Listening

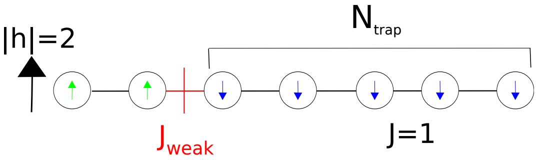
Thank You

Aside I: why not just measure multi-qubit Rabbi Oscillations?

- Maximum annealing rate ($20\,\mu s$ for whole anneal) is too slow compared to decoherence time of $150\,ns$ [2]
- Annealing rate is a hardware limitation, not an artificial one imposed by the user API
- Optimal annealing rate for computation is also faster than what the hardware allows [3]

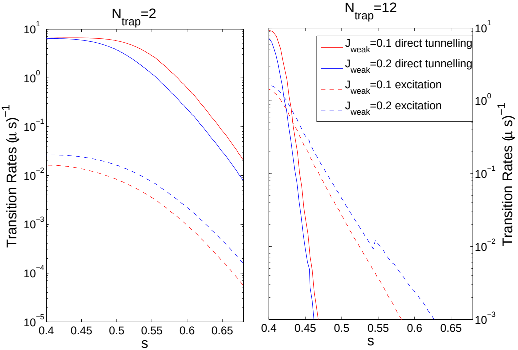
Aside II: domain wall escape from weak link

- Simpler version of experiment with single domain wall placed on weak link



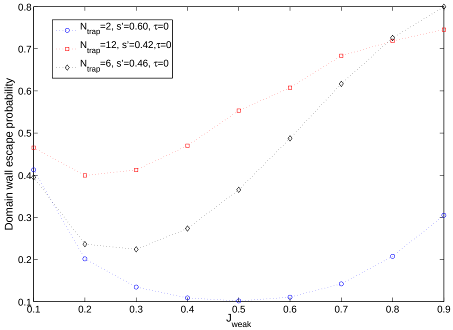
- Activated hopping competes with quantum tunneling
- Activation suppressed for lower J_{weak}
- Tunneling enhanced as J_{weak} becomes closer to zero

Aside II: tunneling versus activation rate



- Tunneling predicted to be the dominant effect at some values of s even for long chains
- We should be able to see this experimentally if we are careful (demonstrated in the next slide)

Aside II: experimental simulation for domain wall escape



- Increasing escape probability is consistent with tunneling, but inconstant with activated process
- Can see this feature even for long chains

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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