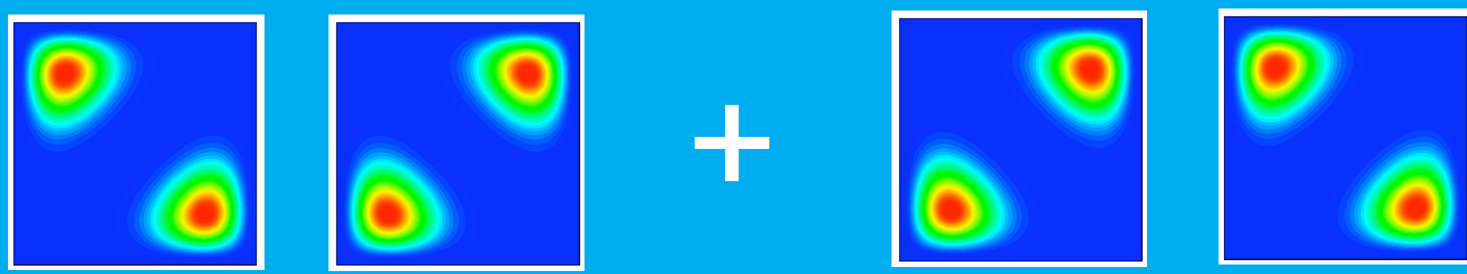
QinetiQ



Two-electron Quantum-dot Qubits

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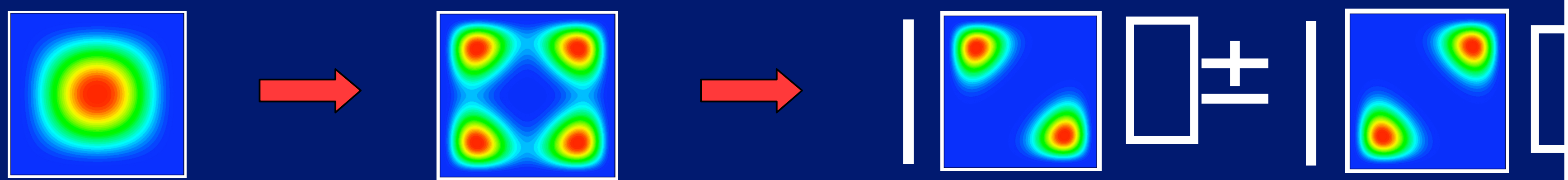
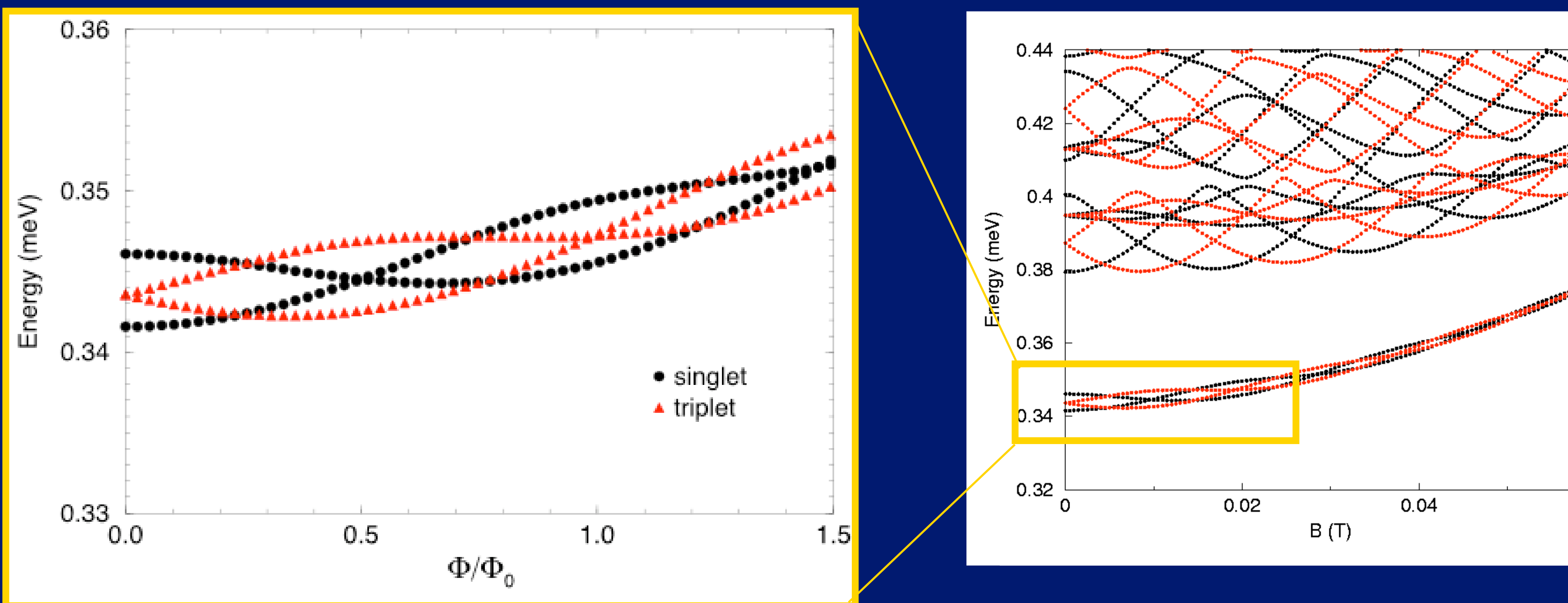
Outline

- Two-electron quantum dots
- Two-electron quantum dot qubits
- Initialisation and single-qubit transformations
- Entanglement and two-qubit transformations via the Coulomb interaction
- Measurement
- Conclusions and Outlook

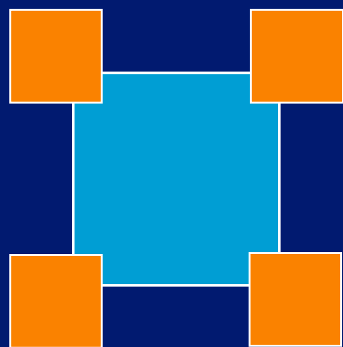
Two-electron quantum dots

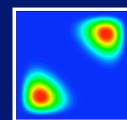


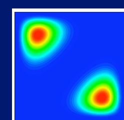


(C. E. Creffield, J. H. Jefferson, S. Sarkar and D. L. Tipton, Phys. Rev. B 62, 7249 (2000)).

Two-electron quantum dot qubits



|□ = |0□ = | ↑□

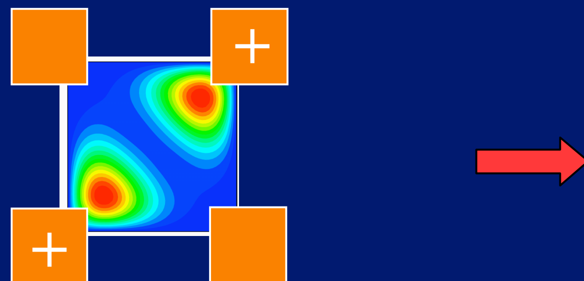
|□ = |1□ = |□□

$$H \,\square \begin{pmatrix} E_0 & \square(\square) \\ \square(\square) & E_1 \end{pmatrix} \qquad \square = \square_0 \cos\left(\square \frac{\square}{\square_0}\right)$$

$$\square \;\; \square\square_z + \square\square_x \qquad \square = \frac{E_1 \,\square\, E_0}{2}$$

$$H = □□_z + □□_x$$

- Initialisation



|0□

- Single qubit transformations

  - *vary □and □with gates and □*

$$□ = 0 \text{ for } t \geq 0 \quad □ \quad |□(t)□ = \cos □t\,|0□ + i \sin □t\,|1□$$

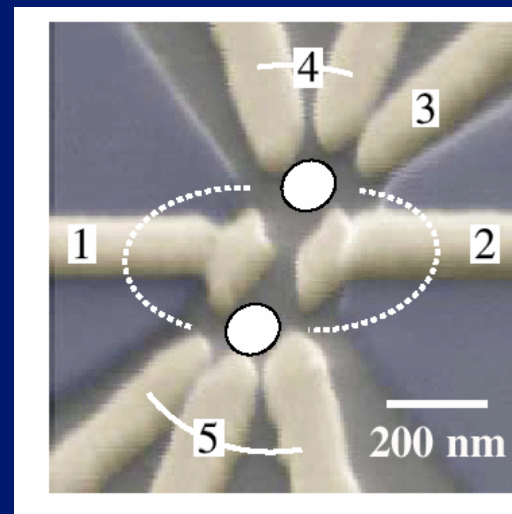
$$□ >> □ \text{ for further time } □$$

$$□ \quad |□(t + □)□□ \cos □t\,|0□ + i e^{□2i□□} \sin □t\,|1□$$

Entanglement and two-qubit transformations via the Coulomb interaction

- Scalable array of qubits with Coulomb interaction:

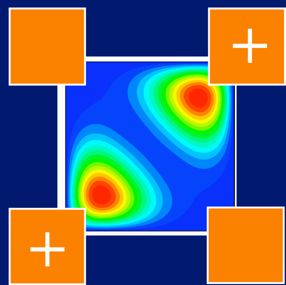
$$\sum_{i,n>0} v_n \sigma_{z,i} \sigma_{z,i+n} \quad \text{where} \quad v_n \sim n^{-6}$$

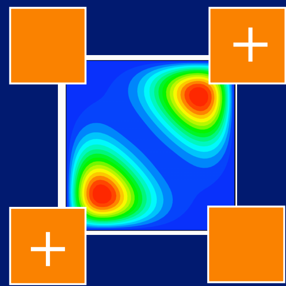


Holleitner et al. PRL Dec' 2001.

- Potential problems:
  - Cannot switch off Coulomb interaction - always entangled?
  - Longer range interactions may not be sufficiently small
  - Single-qubit interactions dominate in general (□>v)

- E.g. start with |0,0>

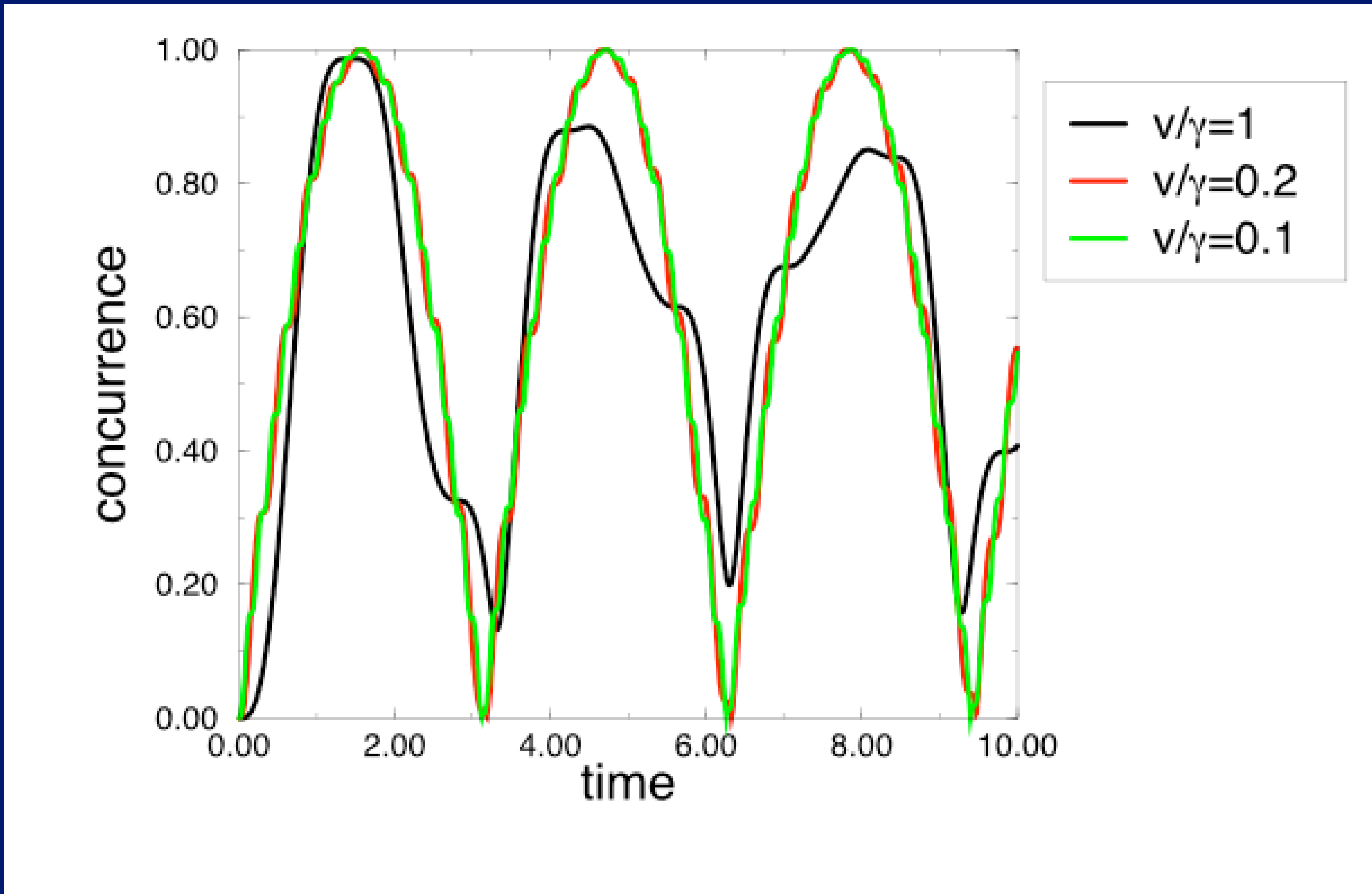




$$\text{Calculate } |\psi(t)\rangle = e^{-\frac{iHt}{\hbar}} |0,0\rangle$$

- Measure of entanglement?
- Concurrence

$$C(t) = 2\,|\ldots|$$



- Oscillations in entanglement due to interplay of and v
- Full entanglement possible - why?

Remove intra-dot (□) oscillations?

- Switch off □(with flux $□_0/2$)
  - –No entanglement! (diagonal)
  - –Use to preserve and control entanglement
- Prepare in single qubit energy eigenstates

$$|\pm□ \frac{|0□\pm|1□}{\sqrt{2}}$$

  - entanglement changes on the scale *t=h/v*
  - States |+,□ □, |□,+□ degenerate, 2-state system

$$e^{□\frac{iHt}{\hbar}}|+,□□□□ \cos\frac{vt}{\hbar}|+,□□□□ i\sin\frac{vt}{\hbar}|□,+□$$

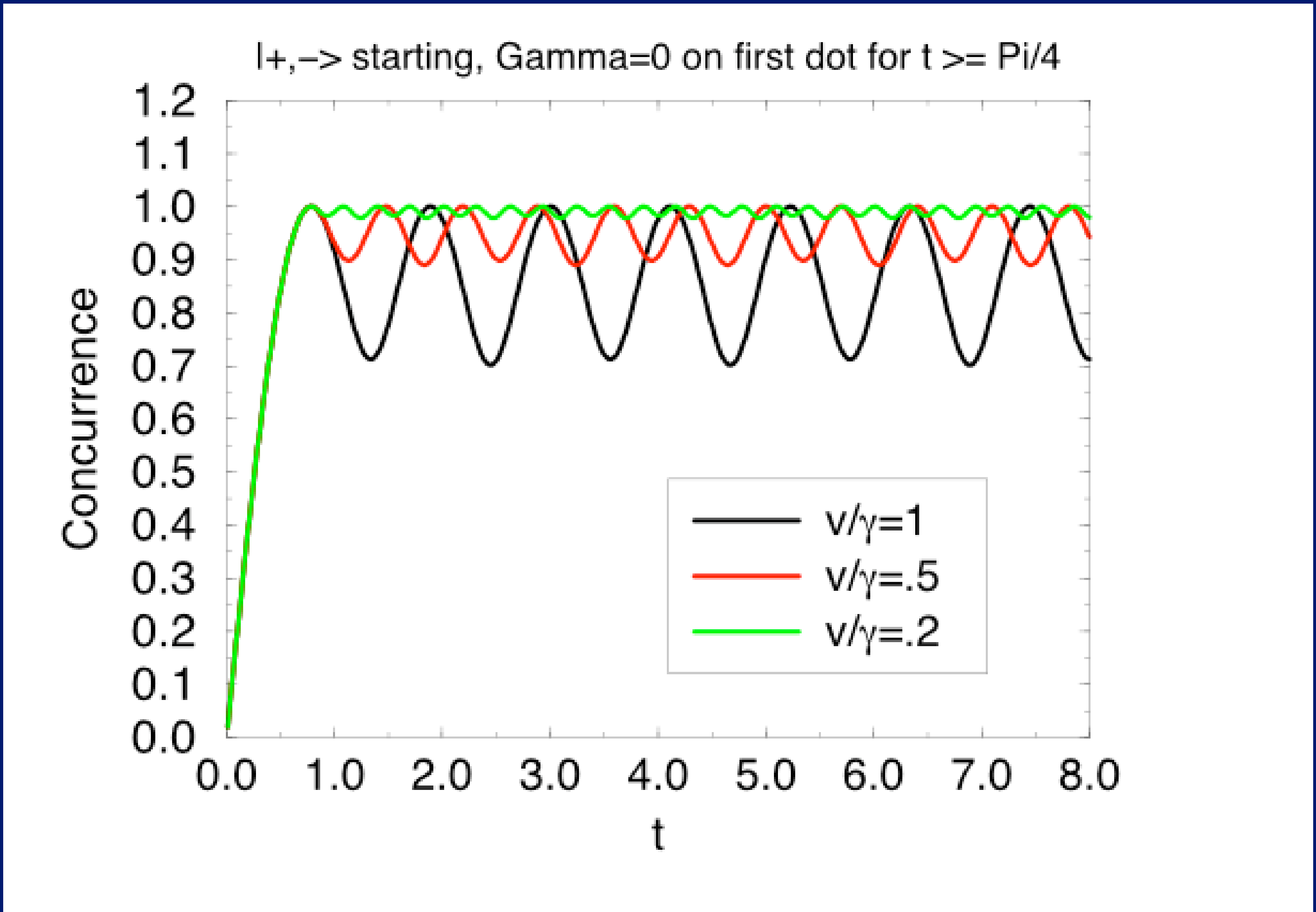
- Maximum entanglement (ROOT SWAP) at *t=h/8v*
- Concurrence

$$C(t) = |\sin\frac{2vt}{\hbar}|$$

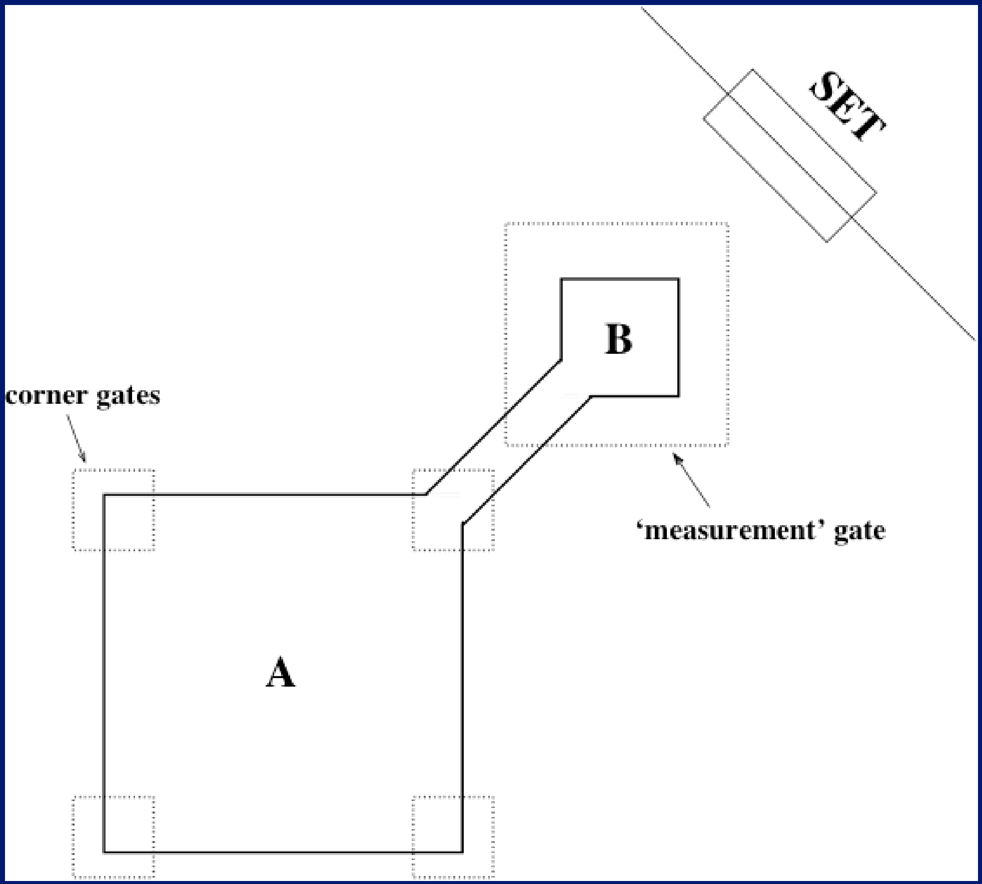
- |□ □state preparation:
  - Decouple neighbours (□=0)
  - Allow to relax to ground state (requires incoherent processes)

- |+ □state preparation:
  - Decouple neighbours
  - Apply flux $□_0$
  - Relax to ground state
  - Remove field (□□ □□)

- Entanglement preservation
  - Remove degeneracy of states |+,□ □and |□,+□
  - e.g. □=0 on one dot


|+,-> starting, Gamma=0 on first dot for t >= Pi/4
Concurrence
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
t
v/γ=1
v/γ=.5
v/γ=.2

Measurement



Conclusions and Outlook

- 2-electron quantum dots basis for scalable qubit array
- Satisfies DiVincenzo's list
- Decoherence uncertain
  - Mainly acoustic phonon emission
  - 'tuned' by material choice and geometry
- Possible realisations in other systems, e.g molecular

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