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LETTERS

Demonstration of controlled-NOT quantum gates on a pair of superconducting quantum bits

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Outline

- Why CNOT-Gates?
- Theoretical Background
- Experimental Realization
- Results

CNOT-Gate

	00	01	10	11
00	1	0	0	0
01	0	1	0	0
10	0	0	0	1
11	0	0	1	0

Input

Output

	00	01	10	11
00	1	0	0	0
01	0	1	0	0
10	0	0	0	1
11	0	0	1	0

- The CNOT gate flips the second qubit if and only if the first qubit is 1.

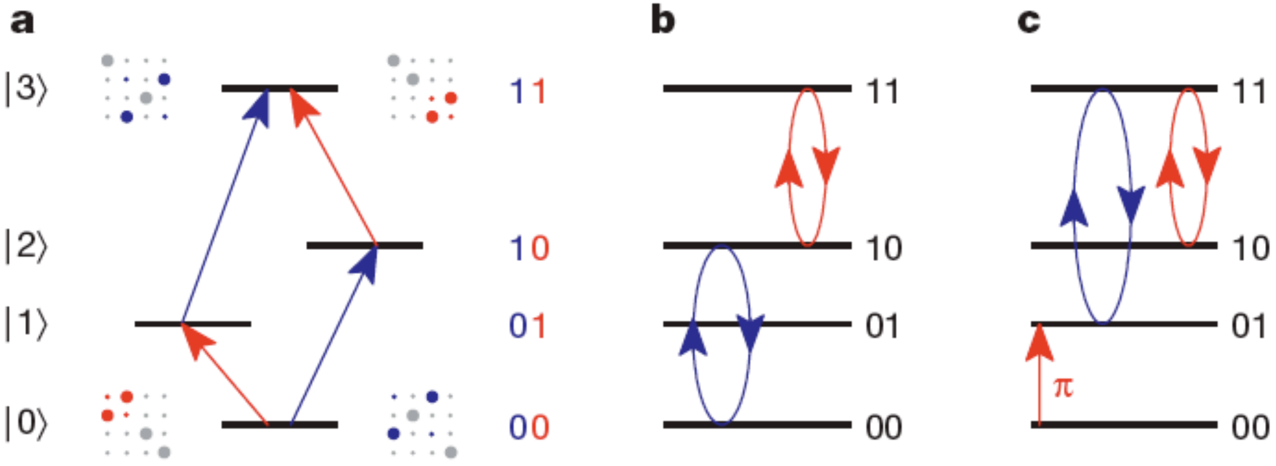
- The resulting value of the second qubit corresponds to the result of a classical XOR gate.

Any quantum circuit can be simulated to an arbitrary degree of accuracy using a combination of CNOT gates and single qubit rotations (plus Hadamard gates for entangling).

Theoretical Background

two-qubit Hamiltonian:

$$H = -\frac{1}{2}\left(\varepsilon_1\sigma_z^1 + \Delta_1\sigma_x^1 + \varepsilon_2\sigma_z^2 + \Delta_2\sigma_x^2\right) + J\sigma_z^1\sigma_z^2$$

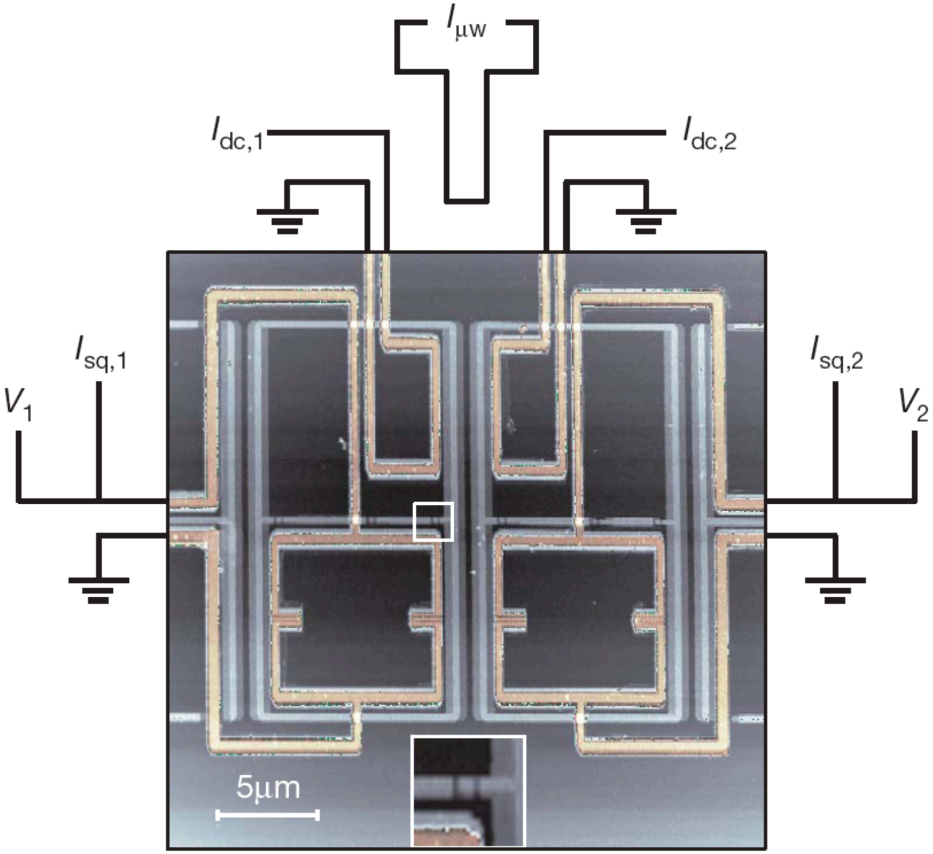


$$R_{1_C 0_T - 1_C 1_T}(\omega,\tau) = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & \cos\frac{\omega\tau}{2} & i\sin\frac{\omega\tau}{2} \\ 0 & 0 & i\sin\frac{\omega\tau}{2} & \cos\frac{\omega\tau}{2} \end{pmatrix}$$

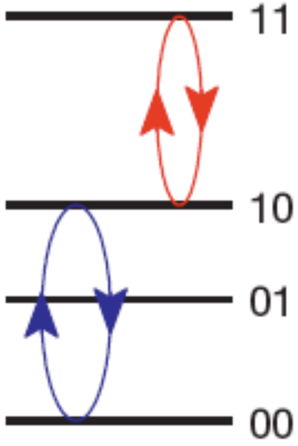
$\Rightarrow$ CNOT - gate for $\omega\tau = \pi$

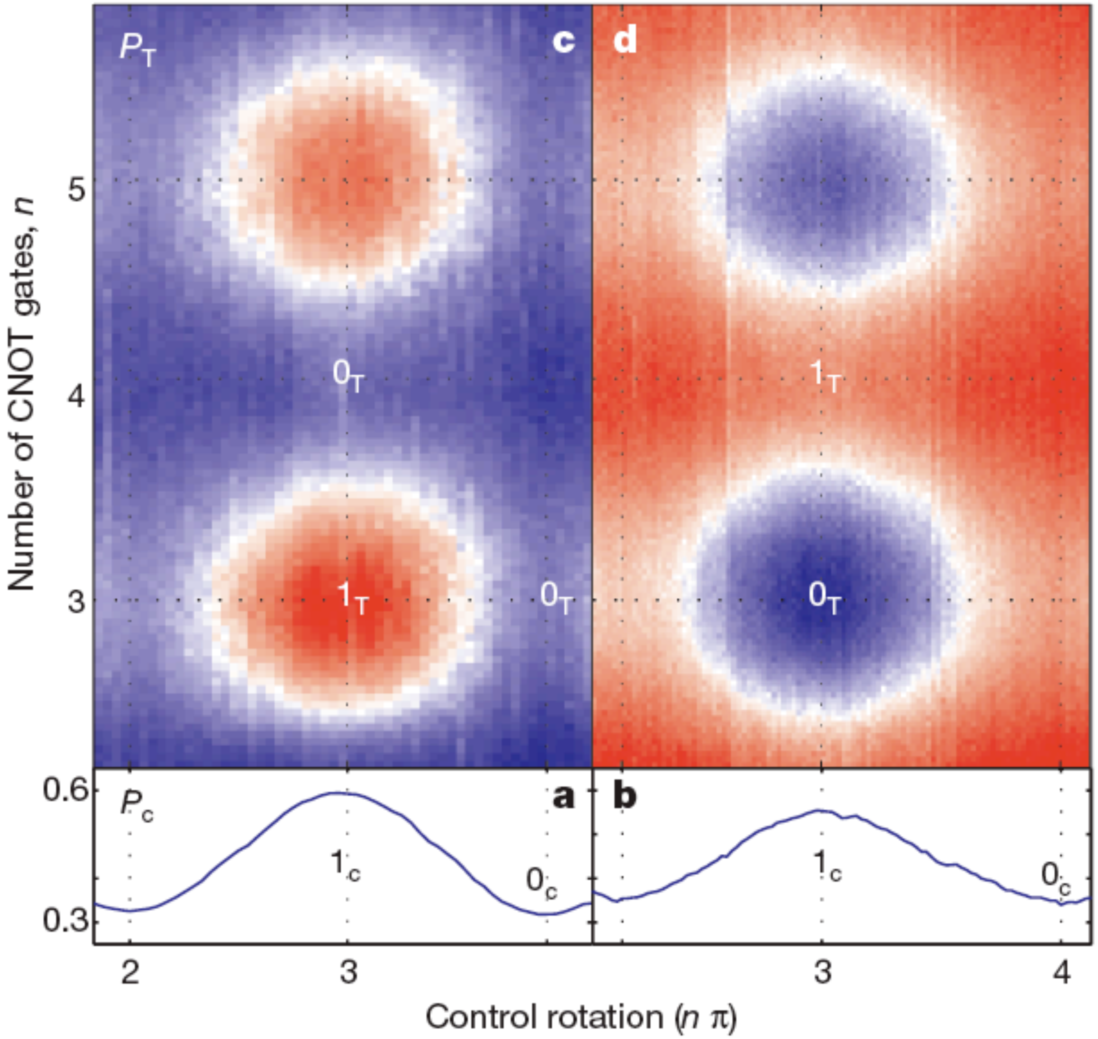
Experimental Realization

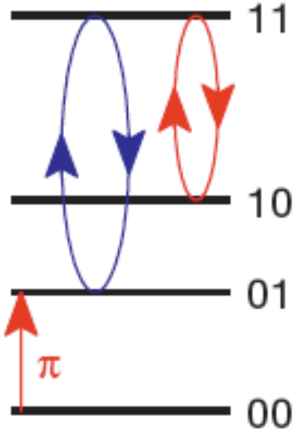
- couple two flux qubits magnetically
- tunability with individual flux biases
- realization of two-qubit operations with microwave pulses
- readout of qubit-states with SQUIDs
- put the whole thing into a dil fridge at 50mK



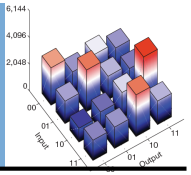
Results

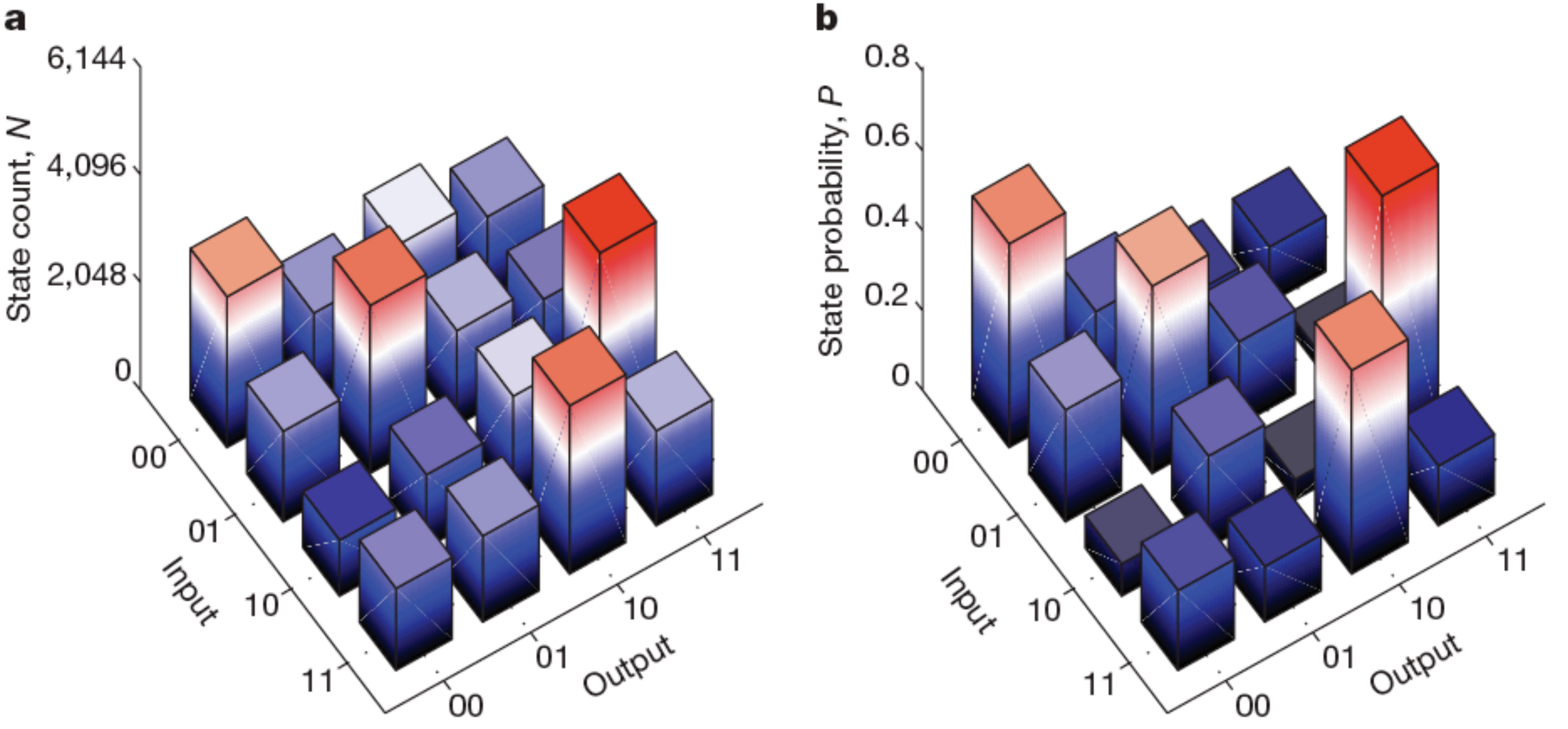

11
10
01
00


P_T
c
d
5
4
3
0_T
1_T
0_T
1_T
0_T
Number of CNOT gates, n
0.6
0.3
P_c
a
b
1_c
0_c
1_c
0_c
2
3
3
4
Control rotation (n π)


11
10
01
π
00

Results





$$CNOT_{\text{exp}} = \begin{pmatrix} 0.51 & 0.22 & 0.13 & 0.14 \\ 0.28 & 0.47 & 0.21 & 0.04 \\ 0.08 & 0.23 & 0.05 & 0.64 \\ 0.20 & 0.14 & 0.51 & 0.15 \end{pmatrix}$$

$\Rightarrow$ fidelity $F = 0.4$ $(F = 1$ in ideal case$)$

Summary & Outlook

- Implementation of the complete set of four two-qubit CNOT-gates

- longer coherence times & optimized detector visibility will lead to higher fidelity

- possibility of implementation of two-qubit algorithms in a solid-state environment

Phase Factors

- phase shift of the states 1_C0_T and 1_C1_T relative to states 0_C0_T and 0_C1_T by execution of $2n$ CNOT-gates
- Ramsey-like interference experiment on n consecutive CNOT-gates