Trapped-Ion Quantum Computers

Ilja Zebergs
Department of Physics and Astronomy, Heidelberg University
(Dated: January 11, 2022)

This seminar talk gives a brief overview on the topic of quantum computing focusing on the physical realisation using the states of trapped ions to process information in a novel way compared to "classical" bit-based computers. While being one of the oldest among other platforms for quantum computing, trapped-ions remain relevant and promising to this day.

I. HISTORY

The idea of quantum computing - to perform calculations using quantum mechanical (QM) systems more efficiently than on a classical computer can be traced back to the 1980s. In his conference talk (1981) Feynman proposed, that some QM machines could drastically improve the efficiency of simulating quantum mechanics due to their natural compatibility with theory [1]. In 1985 Deutsch described the concept of the "universal quantum computer" as an abstraction of a Turing machine [2]. In 1992 an algorithm showing the use of quantum parallelism to exponentially outperform a classical computer (known as Deutsch-Josza algorithm after its authors) was published [3]. In 1995 a blueprint for quantum hardware using a chain of trapped ions was published by Cirac and Zoller [4]. The same year first experimental implementations of some fundamental operations according to this blueprint were shown [5].

II. QUANTUM CIRCUITS AND ALGORITHMS

A common theoretical framework for constructing quantum algorithms is qubit-based quantum circuit model inspired by logic circuits in classical computing [6]. A fundamental unit of information is a quantum bit (qubit) - a QM two-state system allowing superpositions. Several such qubits form a quantum register and operations are described by the quantum gates - unitary operators acting on the register. The algorithms are constructed as a sequence of quantum gates forming a quantum cicruit. Existing algorithms include e.g. factoring with exponential speed-up [7], database search with quadratic speed-up [8] as well as different simulation and optimisation schemes [9].

III. TRAPPED-ION HARDWARE

Such quantum computer can be realised using any QM system fulfilling the DiVincenzo criteria [10]. A possible realisation discussed herein utilises two (meta-)stable atomic states of ions, stored in a chain inside a linear Paul trap [4]. To avoid thermal population of the excited states and achieve a decent spatial localisation, the ions are cooled using laser-cooling techniques e.g. Doppler-cooling and resolved sideband cooling. [11]

The computational cycle consists of initialisation in a (simple) well-known state, control sequence performing the quantum circuit and the read-out of the register, resulting in one of possible bit-strings [12]. Control sequence generally consists out of many-qubit gates, which can be constructed out of single-qubit gates and one suitable entangling two-qubit gate (universal set of gates) [6].

Control (gates) is realised using certain electromagnetic pulses, typically in optical or radio-frequency range [12]. A common way to entangle two ions is to utilise the collective motional modes of the ion chain mediated via Coulomb interaction e.g. Cirac-Zoller, Mølmer–Sørensen gates [4], [11]. Initialisation is performed using optical pumping and the read-out is realised via collecting state-dependent fluorescence [11].

A scheme of an examplary trapped-ion hardware (11-qubit IonQ quantum computer for research purposes [13]) can be seen in Fig. 1.

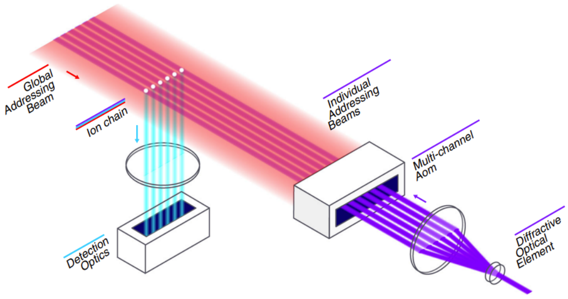

FIG. 1: An exemplary trapped-ion hardware scheme: The ions are trapped in a linear surface trap, hyperfine splitting of their ground state is used as qubits. The ions are addressed by two Raman laser beams: a global beam shines on all ions constantly and the second beam is split into individual beams for each ion, those are controlled using a multi-channel AOM. The fluorescence is collected using additional optics and detectors. Source: [13]

[1] R. P. Feynman. Simulating physics with computers (1982) Int. J. Theor. Phys. 21, 467–488. doi: 10.1007/BF02650179

[2] D. Deutsch. Quantum theory, the Church–Turing principle and the universal quantum computer (1985) Proc. R. Soc. Lond. A40097–117. doi:10.1098/rspa.1985.0070

[3] D. Deutsch and R. Jozsa. Rapid solution of problems by quantum computation (1992) Proc. R. Soc. Lond. A439553–558. doi:10.1098/rspa.1992.0167

[4] J. I. Cirac and P. Zoller. Quantum Computations with Cold Trapped Ions (1995) Phys. Rev. Lett. 74, 4091. doi:10.1103/PhysRevLett.74.4091

[5] C. Monroe, D. M. Meekhof, B. E. King, W. M. Itano, and D. J. Wineland. Demonstration of a Fundamental Quantum Logic Gate (1995) Phys. Rev. Lett. 75, 4714. doi:10.1103/PhysRevLett.75.4714

[6] M. Nielsen and I. Chuang. Quantum Computation and Quantum Information: 10th Anniversary Edition (2010) Cambridge University Press. doi:10.1017/CBO9780511976667

[7] P. W. Shor. Polynomial-Time Algorithms for Prime Factorization and Discrete Logarithms on a Quantum Computer (1997) SIAM J. Sci. Statist. Comput. 26. doi:10.1137/S0097539795293172

[8] L. K. Grover. A fast quantum mechanical algorithm for database search (1996) STOC '96: Proceedings of the twenty-eighth annual ACM symposium on Theory of Computing. doi:10.1145/237814.237866

[9] Qiskit Textbook. https://qiskit.org/textbook

[10] D. P. DiVincenzo. The Physical Implementation of Quantum Computation (2000) Fortschr. Phys. 48: 771-783. doi:10.1002/1521-3978(200009)48:9/11<771::AID-PROP771>3.0.CO;2-E

[11] H. Häffner, C.F. Roos, R. Blatt. Quantum computing with trapped ions (2008) Phys. Rep. 469, 155-203. doi:10.1016/j.physrep.2008.09.003

[12] C. D. Bruzewicz, J. Chiaverini, R. McConnell, J. M. Sage. Trapped-ion quantum computing: Progress and challenges (2019) Appl. Phys. Rev. 6, 021314. doi: 10.1063/1.5088164

[13] K. Wright, K. M. Beck, S. Debnath, J. M. Amini, Y. Nam, N. Grzesiak, J.-S. Chen, N. C. Pisenti, M. Chmielewski, C. Collins, K. M. Hudek, J. Mizrahi, J. D. Wong-Campos, S. Allen, J. Apisdorf, P. Solomon, M. Williams, A. M. Ducore, A. Blinov, S. M. Kreikemeier, V. Chaplin, M. Keesan, C. Monroe, J. Kim Benchmarking an 11-qubit quantum computer (2019) Nature Communications. doi:10.1038/s41467-019-13534-2