The First Steps Toward Realization of Quantum-Logic at NIST

The starting point in the development of practical quantum-logic systems at NIST involved the convergence to two lines of study. Beginning in the early '80s, Feynman [1] and Benioff speculated on the possibility of using quantum systems to perform (reversible) computation. Deutsch [2] expanded on these ideas, showing that certain computations could be performed more efficiently using quantum systems. In 1994, Peter Shor [3] made a significant advance when he developed a quantum-logic algorithm that could factor large numbers efficiently. But no one had yet devised a practical approach for building a quantum computer.

During this same period, Wineland and his colleagues in the Ion Storage Group at NIST, Boulder, Colorado, were working on laser-cooled ions stored in electromagnetic traps for high-performance frequency standards. There are many advantages to be gained by using stored ions for this application, but one disadvantage is that the most promising approach uses only a few ions, and the signal-to-noise ratio is thus small. In order to deal with this problem, the Ion Storage Group developed a concept for reducing the noise below the usual quantum limit [4,5] through what can be called "spin squeezing," [6] a process more generally referred to as "quantum entanglement." An optimal strategy was later developed by the group [7]. To establish the precise state control needed to produce useful entanglements, the group developed methods for cooling trapped ions to the zero-point energy of motion using side-band cooling methods [8,9].

In 1995, Cirac and Zoller at Innsbruck University, stimulated by discussions presented by Ekert (Oxford University) [10], made the critical link between the quantum-logic work and the cooled-ion work [11] by suggesting that linear ion traps could serve as a means for realization of a quantum computer. Their paper clearly showed that the systems already in use at NIST could be applied to quantum logic, and nearly immediately the Ion Storage Group demonstrated the first quantum-logic gate [12]. Impetus was later added to the burgeoning field by the demonstration of quantum entanglement of 4 ions using a single laser pulse [13], a state-preparation concept proposed the year before by Mølmer and Sørensen [14]. This method greatly simplifies the preparation of the desired entanglements.

In a short editorial note in Nature [15], Blatt pointed out that the entanglement of 4 ions is "not just an incremental achievement," since the technique is scalable to much larger numbers of entangled particles. He also distinguished the ion implementation of quantum logic from other work on entangled atoms and photons where "entanglement is concluded from post-selection of randomly occurring coincidences rather than quantum state engineering." For such post selection, the probability of finding a given correlation drops exponentially with the number of entangled particles.

In summary, as happens in most scientific innovations, a number of pieces had to come together to arrive at the successful demonstration, in this case the engineered entanglement of 4 ions using a single laser pulse. Theoretical interest in quantum computation had become well established. Wineland and his colleagues in the Ion

Storage Group had developed laboratory systems showing the requisite coherences, and they were on their way to entangling ions, so that they could improve their frequency standards. Their work was then greatly stimulated by the quantum-logic suggestion of Cirac and Zoller giving them even stronger motivation for entangling their ions. Finally, the state preparation proposed by Mølmer and Sørensen provided a tool that greatly simplified their seminal experimental demonstration.

For a technical review of the issues underlying coherent quantum manipulations of trapped ions see "Experimental Issues in Coherent Quantum-State Manipulation of Trapped Atomic Ions," D.J. Wineland, C. Monroe, W.M. Itano, D. Leibfried, B.E. King, and D.M. Meekhof (PDF, 683 kB) J. Res. NIST **103**, 259 (1998).

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