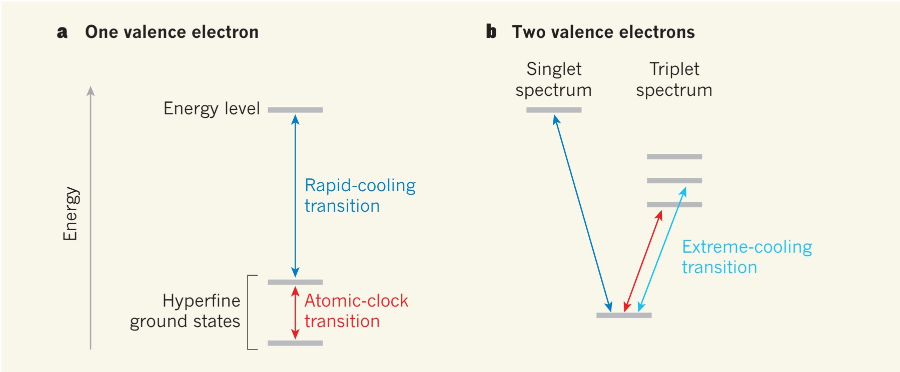

Figure 1 | Atomic energy-level structures. **a**, Atoms that contain one outer (valence) electron have a rather simple structure of electronic energy levels. Transitions of electrons between certain levels can be used to rapidly cool the atoms, whereas transitions between two levels, called hyperfine ground states, can be used to build a microwave-frequency atomic clock. **b**, Atoms that contain two valence electrons, such as strontium and ytterbium, have two separate energy-level spectra: a singlet spectrum and a triplet spectrum. These atoms have transitions that can be used for rapid cooling, as in one-valence-electron atoms. But they also have transitions that can be used in optical atomic clocks and to reach extremely low temperatures. Three papers[2–4] now report the cooling and confinement of individual strontium and ytterbium atoms.

rapid cooling. But they also have transitions that can be used to reach even lower temperatures. Such transitions are not present in alkali atoms (Fig. 1).

The demonstration of arrays of two-valence-electron atoms is an exciting development for other reasons. In the International System of Units (SI), the second is currently defined using the transition between two energy levels called hyperfine ground states in an atom of the alkali element caesium. This transition is associated with the emission or absorption of microwave-frequency light. However, advances in the past decade have shown that higher-accuracy atomic clocks can be built using transitions in atoms or ions at optical frequencies. The atoms that currently provide the most precise optical atomic clocks in the world[8] are the same as those that have now been individually trapped: strontium and ytterbium.

The new results have two implications for the development of future atomic clocks. In current practice, such clocks are based on lattices that have ensembles of up to a thousand atoms at each lattice site. Within each site, the atoms are randomly distributed, and the weak, but non-negligible, interactions between atoms contribute to uncertainty in time readings obtained from the clock. The ability to build arrays of strontium and ytterbium atoms one atom at a time will enable the spatial distribution of the atoms, and therefore their interactions, to be engineered in ways that could reduce sources of uncertainty.

The second implication for clock development is intimately connected to the potential use of strontium and ytterbium atoms as quantum bits (qubits) in quantum-information processing. There are several options for qubit encoding, because these atoms have both fermionic and bosonic isotopes — isotopes whose total numbers of protons and neutrons are odd and even, respectively. For the fermionic isotopes, qubits can be encoded in energy levels known as Zeeman substates. This encoding could involve a single qubit as in ytterbium-171, which has two substates, or many qubits as in strontium-87, which has ten substates[9]. For the bosonic isotopes, qubits can instead be encoded in the energy levels that form the basis of the optical atomic clock.

Once qubits have been encoded in suitable energy levels, interactions between qubits can be engineered to carry out operations called quantum logic gates and to produce quantum states that are entangled (correlated in a non-classical way). This engineering could be achieved using collisional interactions, as has been demonstrated for alkali atoms[10], or by using long-range interactions between atoms that are in excited 'Rydberg' states[6]. The latter interactions are the leading contender for quantum logic gates based on neutral-atom qubits.

Alternatively, many-atom entangled quantum states could be produced directly, without resorting to a laborious sequence of pairwise interactions, using methods known as Rydberg dressing techniques[11]. Irrespective of the approach chosen, the availability of entangled atoms would have the potential for achieving clock precision in which the uncertainty is inversely proportional to the number of atoms — a substantial improvement over the usual case of uncorrelated atoms, in which the uncertainty is inversely proportional to the square root of the number of atoms.

There is good reason to think that, with further development, arrays of single two-valence-electron atoms will lead to advances in optical atomic clocks. Although the focus has been on neutral-atom clocks, those based on ions have comparable accuracy, but their stability is limited because they use only a single ion. Arrays of single neutral atoms could

50 Years Ago

A two-armed bandit is two one-armed bandits. Suppose that you are playing a two-armed bandit and that at each play you are only interested in whether you win or lose. If the probabilities of winning are constant for a particular machine from one play to another, but are different between the machines and in any case are unknown to you and if, moreover, you can only remember what happened for the last *r* plays, what strategy should you adopt if your aim is to maximize your number of wins? … Sequential decision problems of essentially this sort occur quite frequently … Smith and Pyke … have developed what appear to be the best decision rules and now S. M. Samuels, in a paper called "Randomized rules for the two-armed bandit with finite memory" … shows that, by a very simple addition to these rules, startlingly better results may be obtained.

From *Nature* 29 March 1969

100 Years Ago

The Marconi Wireless Telegraph Co. is to be congratulated on having established experimental wireless telephonic communication between Clifden … in Ireland, and Cape Grace, in Canada … The improvements which have been made in thermionic valves — for instance, the reduction of the air-pressure in the valve to the one-hundred-millionth of a millimetre of mercury — have increased their sensitivity enormously. In addition, by connecting them "in cascade" there appears also to be no limit to the sensitivity that can be attained … Wireless telephone transmission is specially interesting, as it is free from many of the defects of ordinary telephony … There seems no reason to doubt that in a short time wireless telephony will be established between every country on the globe.

From *Nature* 27 March 1919