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Distinctive features are very similar to those observed in the ~2500-Ma Mt. McRae Shale, and their age is supported by more thorough analytical protocols (24). The discovery and careful analysis of biomarkers in rocks of still greater age and of different Archean environments will potentially offer new insights into early microbial life and its evolution.

References and Notes

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REPORTS

Josephson Persistent-Current Qubit
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A qubit was designed that can be fabricated with conventional electron beam lithography and is suited for integration into a large quantum computer. The qubit consists of a micrometer-sized loop with three or four Josephson junctions; the two qubit states have persistent currents of opposite direction. Quantum superpositions of these states are obtained by pulsed microwave modulation of the enclosed magnetic flux by currents in control lines. A superconducting flux transporter allows for controlled transfer between qubits of the flux that is generated by the persistent currents, leading to entanglement of qubit information.

In a quantum computer, information is stored on quantum variables such as spins, photons, or atoms (1–3). The elementary unit is a two-state quantum system called a qubit. Computation is performed by the creation of quantum superposition states of the qubits and by controlled entanglement of the information on the qubits. Quantum coherence must be preserved

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In superconductors, all electrons are condensed in the same macroscopic quantum state, separated by a gap from the many quasi-particle states. This gap is a measure for the strength of the superconducting effects. Superconductors can be weakly coupled with Josephson tunnel junctions (regions where only a thin oxide separates them). The coupling energy is given by $E_F(1 - \cos \gamma)$, where the Josephson energy $E_F$ is proportional to the gap of the superconductors divided by the normal-state tunnel resistance of the junction and $\gamma$ is the gauge-invariant phase difference of the order parameters. The current through a Josephson junction is equal to $I_c \sin \gamma$, with $I_c = (2e/h) E_F$, where $e$ is the electron charge and $h$ is Planck’s constant divided by $2\pi$. In a Josephson junction circuit with small electrical capacitance, the numbers of excess Cooper pairs on islands $n_x, n_y$ and the phase differences $\gamma, \gamma_y$ are related as noncommuting conjugate quantum variables (10). The Heisenberg uncertainty between phase and charge and the occurrence of quantum superpositions of charges as well as phase excitations (vortexlike fluxoids) have been demonstrated in experiments (11). Coherent charge oscillations in a superconducting quantum box have recently been observed (12). Qubits for quantum computing based on charge states have been suggested (13, 14). However, in actual practice, fabricated Josephson circuits exhibit a high level of static and dynamic charge noise due to charged impurities. In contrast, the magnetic background is clean and stable. Here, we present the design of a qubit with persistent currents of opposite sign as its basic states. The qubits

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can be driven individually by magnetic microwave pulses; measurements can be made with superconducting magnetometers [superconducting quantum interference devices (SQUIDs)]. They are decoupled from charges and electrical signals, and the known sources of decoherence allow for a decoherence time of more than 1 ms. Switching is possible at a rate of 100 MHz. Entanglement is achieved by coupling the flux, which is generated by the persistent current, to a second qubit. The qubits are small (of order 1 \mu m), can be individually addressed, and can be integrated into large circuits.

Our qubit in principle consists of a loop with three small-capacitance Josephson junctions in series (Fig. 1A) that encloses an applied magnetic flux \( \Phi_0 \), and the third junction has \( \alpha E_f \), where \( \alpha = 0.75 \). This system has two (meta)stable states 10> and 11> with opposite circulating persistent current. The barrier splitting is determined by the offset from \( \Phi_0/2 \) of the flux. The barrier between the states depends on the value of \( \alpha \). The qubit is operated by resonant microwave modulation of the enclosed magnetic flux by a superconducting control line (indicated in red). The barrier splitting is determined by the offset from 0.5 and is given by the persistent current. All operations on qubits are performed with suppressed \( \alpha \) action and for an adiabatic increase of the tunnel barrier between qubit states to facilitate the measurement.

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The four-junction version (Fig. 1B) allows for coupling of qubits, it is much smaller than the flux quantum and only slightly changes the picture here. The system is composed of two loops with equal areas; a magnet supplies a static flux \( 0.330\Phi_0 \) (indicated in red). The microwave current \( I_c \), which is supplied by a superconducting control line (SQUID) circuit. There are two loops with equal areas; a magnet supplies a static flux \( 0.330\Phi_0 \) (indicated in red). Each unit cell has two minima \( I_{\text{in}} \) and \( I_{\text{out}} \) with left- and right-handed circulating currents of about \( 0.75I_0 \) at approximate \( \gamma_1, \gamma_2 \) values of \( \pm 0.27\pi \). The minima would have been symmetric for \( f_1 + f_2 = 1 \), which corresponds to a three-junction loop enclosing half a flux quantum. The set of all \( L \) minima yields one qubit state and the set of \( R \) minima the other. In \( \gamma_1, \gamma_2 \) space, there are saddle-point connections between \( L \) and \( R \) minima as indicated with red (intracell, in) and blue lines (intercell, out). Along such trajectories, the system can tunnel between its macroscopic quantum states. The Josephson energy along the trajectories is plotted in Fig. 2B. The saddle-point energies \( U_{\text{in}} \) and \( U_{\text{out}} \) depend on \( \alpha \) and \( f_2 \); lower SQUID coupling gives lower \( U_{\text{in}} \) but higher \( U_{\text{out}} \). For \( 2\alpha \cos (f_2\pi) < 0.5 \), the barrier for intracell tunneling has disappeared, and there is only one minimum with zero circulating current.

Motion of the system in \( \gamma_1, \gamma_2 \) space can be discussed in analogy with motion of a mass-carrying particle in a landscape with periodic potential energy. Motion in phase space leads to voltages across junctions. The kinetic energy is the associated Coulomb charg-

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**Fig. 1.** Persistent current qubit. (A) Three-junction qubit. A superconducting loop with three Josephson junctions (indicated with crosses) encloses a flux that is supplied by an external magnet. The flux is \( f \Phi_0 \), where \( \Phi_0 \) is the superconducting flux quantum and \( f \) is 0.495. Two junctions have a Josephson coupling energy \( E_f \), and the third junction has \( \alpha E_f \), where \( \alpha = 0.75 \). This system has two (meta)stable states 10> and 11> with opposite circulating persistent current. The barrier splitting is determined by the offset from \( \Phi_0/2 \) of the flux. The barrier between the states depends on the value of \( \alpha \). The qubit is operated by resonant microwave modulation of the enclosed magnetic flux by a superconducting control line (indicated in red). (B) Four-junction qubit. The top junction of (A) is replaced by a parallel junction (SQUID) circuit. There are two loops with equal areas; a magnet supplies a static flux \( 0.330\Phi_0 \) to both. Qubit operations are performed with currents in superconducting control lines (indicated in red) on top of the qubit, separated by a thin insulator. The microwave current \( I_c \), which is supplied by a superconducting control line (SQUID) circuit. There are two loops with equal areas; a magnet supplies a static flux \( 0.330\Phi_0 \) (indicated in red) on top of the qubit, separated by a thin insulator.

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**Fig. 2.** Josephson energy of qubit in phase space. (A) Energy plotted as a function of the gauge-invariant phase differences \( \gamma_1 \) and \( \gamma_2 \) across the left and right junctions of Fig. 1A. The energy is periodic with period \( 2\pi \). There are two minima in each unit cell, for the center cell indicated with \( I_{\text{in}} \) and \( I_{\text{out}} \). The trajectory between \( I_{\text{in}} \) and \( I_{\text{out}} \) is indicated in red; the trajectories between \( R_{\text{in}} \) and \( R_{\text{out}} \) in next-neighbor cells \( L_{\text{in}} \) and \( L_{\text{out}} \) are indicated in blue. (B) Energy along the red and a blue trajectory of (A). For the parameters chosen, the blue saddle point is substantially higher than the red saddle point. As a result, tunneling from cell to cell is suppressed and the qubit is decoupled from electrical potentials. (solid lines) \( I_{\text{in}} = I_{\text{out}} = 0 \) (see Fig. 1B), (dashed lines) Control current \( I_c \) reduces the flux in the SQUID loop by \( \delta_{\text{g}} = -0.02 \) times the flux quantum. Similarly, when \( \alpha \) is increased (decreased) from 0.75, the red saddle point goes up (down), whereas the blue saddle point goes down (up).
ing energy of the junction capacitances. The mass is proportional to the junction capacitance $C$ because other capacitance elements are small. The effective mass tensor has principal values $M_{xx}$ and $M_{yy}$ in the $\gamma_1 - \gamma_2 = 0$ and $\gamma_1 + \gamma_2 = 0$ directions. For the chosen values of the circuit parameters, these principal values are $M_{xx} = h^2/(4E_C)$ and $M_{yy} = h^2/(4E_C)$, where the charging energy is defined as $E_C = e^2/2C$. The system will perform plasma oscillations in the potential well with frequencies $\omega_{pl} \approx 1.3(E_CE_x)^{1/2}$ and $\omega_{pl} \approx 2.3(E_xE_C)^{1/2}$. The tunneling matrix elements can be estimated by calculation of the action in the Wentzel-Kramers-Brillouin approximation. For tunneling within the unit cell between the minima L and R, the matrix element is $t_{out} \approx \omega_{pl} \exp(-0.64(E_xE_C)^{1/2})$. For tunneling from cell to cell, the matrix element is $t_{out} \approx \omega_{pl} \exp(-1.5(E_xE_C)^{1/2})$. For the qubit, a subtle balance has to be struck: The plasma frequency must be small enough relative to the barrier height to have well-defined states with a measurable circulating current but large enough (small enough mass) to have substantial tunneling. The preceding qualitative discussion has been confirmed by detailed quantitative calculations in phase space and in charge space (13). From these calculations, the best parameters for qubits can be determined. In practice, it is possible to controllably fabricate aluminum tunnel junctions with chosen $E_x$ and $E_C$ values in a useful range.

It is strongly desirable to suppress the intercell tunneling $t_{out}$. This suppression leads to independence from electrical potentials, even if the charges on the islands are conjugate quantum variables to the phases. The qubit system in phase space is then comparable to a crystal in real space with non-overlapping atomic wave functions. In such a crystal, the electronic wave functions are independent of momentum; similarly, charge has no influence in our qubit.

Mesoscopic aluminum junctions can be reliably fabricated by shadow evaporation with critical current densities up to 500 A/cm$^2$. In practice, a junction of 100 nm$^2$ by 100 nm$^2$ has $E_x$ around 25 GHz and $E_C$ around 20 GHz. A higher $E_x/E_C$ ratio can be obtained by increasing the area to which $E_x$ is proportional and $E_C$ is inversely proportional.

A practical qubit would, for example, have junctions with an area of 200 nm$^2$ by 400 nm$^2$, $E_x \sim 200$ GHz, $E_x/E_C \sim 80$, much splitting $\Delta E \sim 10$ GHz, barrier height around 35 GHz, plasma frequency around 25 GHz, and tunneling matrix element $t_{out} \sim 1$ GHz. The matrix element for undesired tunneling is smaller than 1 MHz. The qubit size would be of order 1 μm; with an estimated inductance of 5 pH, the flux generated by the persistent currents is about $10^{-3} \Phi_0$.

To calculate the dependence of the level splitting on $f_1$ and $f_2$, we apply a linearized approximation in the vicinity of $f_1 = f_2 = 1/3$, defining $F$ as the change of $U_1$ away from the minimum of $U_1(\gamma_1,\gamma_2)$. This yields $F/E_x \approx 1.2[2(f_1 - 1/3) + (f_2 - 1/3)]$. The level splitting without tunneling would be $2F$. With tunneling, symmetric and antisymmetric combinations are created; the level splitting is now $\Delta E = 2(F^2 + T_{out}^2)^{1/2}$. As long as $F \gg T_{out}$, the newly formed eigenstates are localized in the minima of $U_1(\gamma_1,\gamma_2)$.

We discuss qubit operations for the four-junction qubit. They are driven by the current $I_{out}$ and $I_{in}$ in the two control lines (Fig. 1B). The fluxes generated in the two loops, normalized to the flux quantum, are $\delta_1 = (I_{out}I_C + I_{in}I_C)\Phi_0$ and $\delta_2 = (I_{out}I_C + I_{in}I_C)\Phi_0$. The control line positions are chosen such that $L_{x1} = 0$ and $L_{x2} = -2I_{in}/3$. When the two loops have equal areas, $f_1 = f_2$ for zero control current. We assume that the qubit states are defined with zero control current and that $\delta_1$ and $\delta_2$ act as perturbations to this system. The effective Hamiltonian operator ($H_{eff}$) in terms of Pauli spin matrices $\sigma_x$ and $\sigma_z$ for the chosen parameters is about

$$H_{eff}\Delta E = (8\delta_1 + 42\delta_2)\sigma_x - (9.28\delta_1 + 8.35\delta_2)\sigma_z,$$

The numerical prefactors follow from the variational analysis of the influence of $\delta_1$ and $\delta_2$ on the tunnel barrier and the level splitting. The terms that contain $\sigma_z$ can be used to induce Rabi oscillations between the two states, applying microwave pulses of frequency $\Delta E/h$. There are two main options, connected to one of the two control lines. Control current $I_{out}$ changes $\delta_1$, which leads to a Rabi oscillation ($\sigma_z$ term) as well as a strong modulation of the Larmor precession ($\sigma_x$ term). As long as the Rabi frequency is far enough below the Larmor frequency, this is no problem. For $\delta_1 = 0.001$, the Rabi frequency is 100 MHz. This mode is the only one available for the three-junction qubit and is most effective near the symmetry point $f = 0.5$ or $f_1 = f_2 = 1/3$. Control current $I_{in}$ is used to modulate the tunnel barrier. Here, the $\sigma_x$ action is suppressed by means of the choice $L_{in}/I_{in} = \delta_2/\delta_1 = -2$. However, a detailed analysis shows that with $\delta_2$ modulation, it is easy to excite the plasma oscillation with frequency $\omega_0$. One has to restrict $\delta_2$ to remain within the two-level system. Values of 0.001 for $\delta_1$ or $\delta_2$ correspond to about 50-pW microwave power at 10 GHz in the control line. These numbers are well within practical range.

The two or more qubits can be coupled by means of the flux that the circulating persistent current generates. The current is about 0.3 μA, the self-inductance of the loop is about 5 pH, and the generated flux is about $10^{-3}\Phi_0$. When a superconducting closed loop (a flux transformer) with high critical current is placed on top of both qubits, the total enclosed flux is constant. A flux change $\Delta \Phi$ that is induced by a reversal of the current in one qubit leads to a change of about $\Delta \Phi/2$ in the flux that is enclosed by the other qubit. One can choose to couple the flux, generated in the main loop of qubit 1, to the main loop of qubit 2 ($\sigma_x\otimes\sigma_x$ coupling) or to the SQUID loop of qubit 2 ($\sigma_x\otimes\sigma_z$ coupling). A two-qubit gate operation is about as efficient as a single qubit operation driven with $\delta_1 = 0.001$. An example of a possible controlled-NOT operation with fixed coupling runs as follows: The level splitting of qubit 2 depends on the state of qubit 1, the values are $\Delta E_{q2}$ and $\Delta E_{q1}$. When Rabi microwave pulses, resonant with $\Delta E_{q2}$, are applied to qubit 2, it will only react if qubit 1 is in its $I > 1$ state. In principle, qubits can be coupled at larger distances. An array scheme as proposed by Lloyd (I, 3), where only nearest neighbor qubits are coupled, is also very feasible. It is possible to create a flux transformer that has to be switched on by a control current (Fig. 3).

The typical switching times for our qubit are 10 to 100 ns. To yield a practical quantum computer, the decoherence time should be at least 100 μs. We can estimate the influence of known sources of decoherence for our system, but it is impossible to determine the real decoherence time with certainty, except by measurement. We discuss
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Energetic Iron(VI) Chemistry: The Super-Iron Battery

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Higher capacity batteries based on an unusual stabilized iron(VI) chemistry are presented. The storage capacities of alkaline and metal hydride batteries are largely cathode limited, and both use a potassium hydroxide electrolyte. The new batteries are compatible with the alkaline and metal hydride battery anodes but have higher cathode capacity and are based on available, benign materials. Iron(VI/III) cathodes can use low-solubility K2FeO4 and BaFeO4 salts with respective capacities of 406 and 313 milliampere-hours per gram. Sup¬
ern iron batteries have a 50 percent energy advantage compared to conventional alkaline batteries. A cell with an iron(VI) cathode and a metal hydride anode is significantly (75 percent) rechargeable.

Improved batteries are needed for various applications such as consumer electronics, communications devices, medical implants, and transportation needs. The search for higher capacity electrochemical storage has focused on a wide range of materials, such as carbonaceous materials (1), tin oxide (2), groupitic electrocatalysts (3), or macroporous minerals (4). Of growing importance are rechargeable (secondary) batteries such as met¬
al hydride (MH) batteries (5), which this year have increased the commercial electric car range to 250 km per charge. In consumer electronics, primary, rather than secondary, batteries dominate. Capacity, power, cost, and safety factors have led to the annual global use of approximately 6 × 1010 alka¬
line or dry batteries, which use electrochemi¬
al storage based on a Zn anode, an aqueous electrolyte, and a MnO2 cathode, and which constitute the vast majority of consumer batteries. Despite the need for safe, inexpensive, higher capacity electrical storage, the aque¬ous MnO2/Zn battery has been a dominant primary battery chemistry for over a century. Contemporary alkaline and MH batteries have two common features: Their storage capacity is largely cathode limited and both use a KOH electrolyte.

We report a new class of batteries, re¬ferred to as super-iron batteries, which contain a cathode that uses a common material (Fe) but in an unusual (greater than 3) va¬lence state. Although they contain the same Zn anode and electrolyte as conventional al¬kaline batteries, the super-iron batteries pro¬vide >50% more energy capacity. In addi¬tion, the Fe(VI) chemistry is rechargeable, is based on abundant starting materials, has a relatively environmentally benign discharge product, and appears to be compatible with the anode of either the primary alkaline or secondary MH batteries.

The fundamentals of MnO2 chemistry continue to be of widespread interest (6). The storage capacity of the aqueous MnO2/Zn

References and Notes