

the inorganic components, the phage are participants rather than bystanders in the assembly process. Relatively small (~20 nm in diameter) particles are easily organized into the layered structure formed by the viral rods, leading to well-populated lines only a few tens of nanometers across spaced by the length of the bacteriophages. Incorporation of various appropriate molecular components could allow this self-assembly process to generate a variety of optical, electronic, or magnetic devices.

References

1. S.-W. Lee *et al.*, *Science* **296**, 892 (2002).
2. L. C. Welsh *et al.*, *Macromolecules* **29**, 7075 (1996).
3. S. M. Yu *et al.*, *Nature* **389**, 167 (1997).

4. M. Muthukumar, C. K. Ober, E. L. Thomas, *Science* **277**, 1225 (1997).
5. R. D. Piner *et al.*, *Science* **283**, 661 (1999).
6. M. Park *et al.*, *Appl. Phys. Lett.* **79**, 257 (2001).
7. E. Jeoung *et al.*, *Langmuir* **17**, 6396 (2001).
8. L. H. Radzilowski, J. L. Wu, S. I. Stupp, *Macromolecules* **26**, 879 (1993).
9. J. T. Chen, E. L. Thomas, S. S. Hwang, C. K. Ober, *Macromolecules* **28**, 1688 (1995).
10. S. R. Whaley *et al.*, *Nature* **405**, 665 (2000).

PERSPECTIVES: PHYSICS

Superconducting Qubits— a Major Roadblock Dissolved?

A. J. Leggett

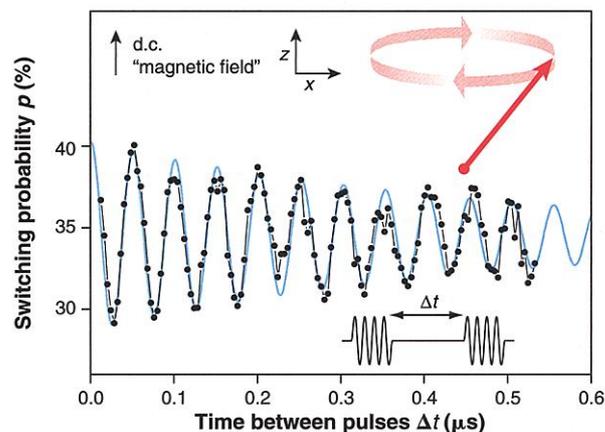
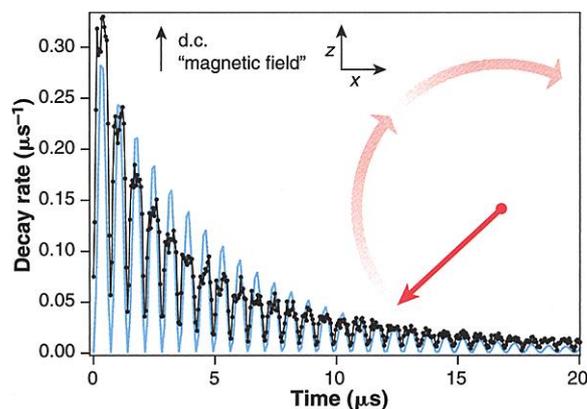
In the race to implement a real quantum computer, systems based on macroscopic electrical circuits incorporating Josephson junctions have until now been something of a dark horse. Such systems may be scalable up to the minimum number of qubits that would make a real-life quantum computer useful. In addition each qubit can be individually addressed by conventional techniques of electrical engineering. However, by the phenomenon of decoherence (1), any irreversible interaction of a quantum-mechanical system with its environment destroys the phase relations between the different branches of its wave function. These phase relations are at the very heart of proposals for quantum computing (2) and decoherence has been thought to be a serious drawback. Two papers in this issue [Yu *et al.* on page 889 (3) and Vion *et al.* on page 886 (4)] have now shown that this view may be too pessimistic.

A qubit—the basic element in a quantum computer—can be formed by any physical system whose motion is effectively restricted to a two-dimensional Hilbert space (that is, whose state is restricted to being an arbitrary superposition of two “basis” states). It is often convenient to represent such a system as a “particle” of spin $1/2$, subject to a fictitious “magnetic field” whose direction we conventionally take to define the z axis; however, in some cases the most easily observable quantity turns out to be the x component of the “spin,” S_x . In any case, what is of most interest in the context of quantum computing is the extent to which the phase relation between the “spin-up” and “spin-down” components of the wave function is preserved, and this turns out to be equivalent to the extent to which the direction of the xy -plane component of the spin vector remains well-defined. The ef-

fect of decoherence in randomizing the relative phase, and thus this direction, is usually quantified by the inverse of the “phase relaxation time” T_ϕ (T_2 in the conventional NMR language), or equivalently by the quantity Q_ϕ , which is half the product of T_ϕ and the (angular) Larmor precession frequency (that is, Q_ϕ is approximately the number of revolutions for which the direction of the xy component of spin re-

mains well-defined). It is generally believed that successful quantum computation requires, as a minimum, that Q_ϕ should be at least of the order of 10^4 . Information on Q_ϕ can be obtained from Rabi-oscillation experiments, in which the system is driven by an rf field with frequency close to the Larmor frequency and the expectation value of the z component of spin is monitored (sufficiently noninvasively) as a function of time, and more directly from “Ramsey-fringe” (free-precession) experiments that effectively measure the expectation value of the x component as a function of the time for which the precession has lasted. In addition to T_ϕ , it is sometimes useful to define the “longitudinal” or “energy” relaxation time T_1 ; in

practice T_1 is almost always longer than T_ϕ . Proposals to use Josephson systems as qubits have up to now mostly concentrated (5) on two specific implementations, the “Cooper-pair box” (“charge qubit”) and the “rf SQUID ring” (“flux qubit”). In the first case, a small superconducting grain is connected to a superconducting reservoir by a Josephson junction. The eigenstates of S_x correspond to states with N and $N + 1$ Cooper pairs (electronic “quasi-molecules”) on the grain. (Other possible states have much higher energies and can be ignored). At a suitable bias voltage on the grain relative to the reservoir, these states are degenerate in the absence of Josephson tunneling, but such tunneling splits them. Using the “spin” analogy, this provides a magnetic field in the z direction. In this system the most serious source of decoherence is believed to be fluctuations in the biasing voltage (“charge noise”); despite this, Nakamura *et al.* (6) were able to perform free-precession experiments



Probing coherence in macroscopic systems. In a Rabi-oscillation experiment (top) the z component of “spin” displays the expected damped sinusoidal behavior. In a Ramsey-fringe experiment (bottom) the x component as probed at a frequency Ω_p shows damped sinusoidal oscillations at the beat frequency $\Omega_p - \Omega_L$ (Ω_L = Larmor frequency).

The author is in the Department of Physics, University of Illinois at Urbana-Champaign, Urbana, IL 61801, USA.

in which they effectively observed a Q_ϕ of order 50. In the second implementation, the “flux qubit,” the system is a superconducting loop, typically of size of the order of a few micrometers, subjected to a suitable external magnetic flux; in this case the S_x eigenstates correspond to different values of the circulating current and hence of the total flux, and the “magnetic field” is provided by collective tunneling between these two states. Fluctuations of the external flux (“flux noise”) are a major source of decoherence, and the only experiments (7, 8) to give evidence for quantum superposition in this system are indirect (spectroscopic) and suggest that the Q_ϕ of the particular systems investigated is too small to be useful.

In neither experiment reported in this issue is the system exactly a “charge qubit” or “flux qubit” as defined above. In the experiment of Yu *et al.*, it is a current-biased Josephson junction (which may be regarded as the system formed by breaking the flux-qubit ring apart and driving a fixed external current through the ends). More significantly, the two energy (“ S_z ”) eigenstates are the ground state and first excited state that correspond to small oscillations of the Cooper-pair configuration (which in the flux-qubit geometry would be tied to the flux) around its metastable equilibrium value. It is thus plausible that

the flux-noise problem (or its analog) should be less severe for this system. The experiment is of the Rabi-oscillation type (see the figure), with the probability of occupation of the upper energy eigenstate measured by its relatively rapid decay out of the metastable well. The Rabi oscillations persist for times of the order of 5 μ s, thereby setting a lower limit on T_1 ; with the assumptions made in the paper it sets the same limit on T_ϕ , and because the Larmor frequency is 16 GHz this would then give a lower limit on Q_ϕ of $\sim 2 \times 10^5$. However, the experiment does not measure Q_ϕ directly.

The experimental system of Vion *et al.* is a “hybrid” charge-flux qubit, cleverly designed so that during periods of free precession it is insensitive to both charge and flux noise, while at the readout stage the control parameters are changed so as to greatly increase the sensitivity to flux. In effect, it is a pure “charge” qubit during the free precession and a “flux” one at readout. Both Rabi-oscillation and Ramsey-fringe experiments were performed on this system, and the latter unambiguously gives a Q_ϕ of at least 2.5×10^4 . It should be noted that the small decoherence rate applies when (and probably because!) the two superposed states are not distinguishable by the value of any macroscopic variable. When they are

converted, by adjustment of the control parameters, into states of appreciably different flux, the rate increases dramatically (although even in the “worst” case Q_ϕ is still of order 50).

The most significant conclusion from these experiments is that whatever the difficulties that may be encountered in the attempt to build a quantum computer with Josephson circuits, the originally most feared one—an intolerable and ineluctable rate of decoherence—need not be among them. In addition, the fact that in the experiment of Vion *et al.* the factor Q_ϕ is large even when the superposed states differ markedly in flux value suggests that the fundamental test of quantum mechanics versus an alternative class of theories proposed in (9) may be feasible in the near future.

References

1. W. H. Zurek, *Phys. Today* **44**, 36 (1991).
2. M. A. Nielsen, I. L. Chuang, *Quantum Computation and Quantum Information* (Cambridge Univ. Press, Cambridge, 2000).
3. Y. Yu, S. Han, X. Chu, S.-I. Chu, Z. Wang, *Science* **296**, 889 (2002).
4. D. Vion *et al.*, *Science* **296**, 886 (2002).
5. Y. Makhlin, G. Schoen, A. Shnirman, *Rev. Mod. Phys.* **73**, 357 (2001).
6. Y. Nakamura, Yu. A. Pashkin, J. S. Tsai, *Nature* **398**, 786 (1999).
7. J. R. Friedman *et al.*, *Nature* **406**, 43 (2000).
8. C. van der Wal *et al.*, *Science* **290**, 773 (2000).
9. A. J. Leggett, A. Garg, *Phys. Rev. Lett.* **54**, 857 (1985).

PERSPECTIVES: MICROBIOLOGY

Subversion of Schwann Cells and the Leper's Bell

Peter J. Brophy

What! dost thou turn away and hide thy face?

I am no loathsome leper; look on me.

—King Henry VI, Part II: Act III, Scene II

In this scene, Shakespeare's Queen Margaret evinces the fear of leprosy widespread in medieval society (see the bottom figure). Her horror is particularly acute as the disease probably killed her husband's grandfather Henry IV in 1413. Elucidating the pathophysiology of leprosy is still an urgent matter, given that conservative estimates put the current number of people afflicted with this tragic disease at more than 2 million. Work by

Rambukkana *et al.* (1), reported on page 927 of this issue, increases our understanding of how *Mycobacterium leprae*, the bacterium that causes leprosy, exploits the biology of peripheral nerves, enabling the colonization of host cells.

Leprosy, also known eponymously as Hansen's disease, was the first human disease shown to be caused by a bacterium. Peripheral nerves, and more specifically the Schwann cells that ensheath them in protective myelin, are the prime targets of this pathogen. Once *M. leprae* is established inside Schwann cells, there is often a strong cell-mediated immune response that causes extensive inflammation and peripheral nerve damage. The attendant paralysis and loss of sensation frequently lead to unintentional mutilation of the hands and feet. In this disease, the immune response is too much, too late.

M. leprae colonizes Schwann cells by attaching to both laminin-2, a protein constituent of the extracellular basal lamina, and its receptor α -dystroglycan, a component of the dystroglycan complex in the Schwann cell plasma membrane (see the top figure) (2). The bacterial ligand that binds to the laminin-dystroglycan complex is the PGL-1 glycolipid found only in *M. leprae* (3). Dystroglycan complexes link the basal lamina to the actin cytoskeleton of Schwann cells through membrane-associated linker proteins called dystrophins (4). They are believed to lend mechanical stability to Schwann cells and the nerve axons that these cells enfold, but they may also transduce signals from the exterior to the interior of the cell. In other tissues, dystroglycan complexes also seem to act as receptors for the hemorrhagic fever pathogens, lymphocytic choriomeningitis virus and Lassa fever virus (5).

Intracellular bacilli are readily observed in the Schwann cells that populate the peripheral nerves of lepers. However, Schwann cells are not all affected in the same way. Myelin-forming Schwann cells seem to be relatively free from *M. leprae* infection, whereas nonmyelinating Schwann cells are heavily colonized. The

The author is in the Department of Preclinical Veterinary Sciences, University of Edinburgh, Summerhall, Edinburgh EH9 1QH, UK. E-mail: peter.brophy@ed.ac.uk