ribosome movement along the mRNA. In prokaryotes, the antibiotics chloramphenicol and erythromycin activate the expression of antibiotic-resistance genes. In eukaryotes, arginine and spermidine inhibit the expression of genes in their respective biosynthetic pathways. In all cases, the cofactor and the nascent peptide act together to halt the ribosome. Chloramphenicol presumably acts through its known binding to the peptidyl transferase center, and erythromycin through its interactions with the ribosome tunnel. The sites of action of arginine and spermidine are unknown, but in light of the results of Gong and Yanofsky, it is attractive to consider that these compounds too might act at the peptidyl transferase center.

Important questions still remain to be answered. How do interactions of the nascent peptide with the ribosome tunnel influence events at the peptidyl transferase center, and vice versa? How general are such mechanisms among different organisms? Regulation by nascent peptides with associated cofactors has been observed only for short nascent peptides that would be entirely within the ribosome. Can cofactor- and peptide-dependent regulation affect translation of internal regions of the long reading frames of genes? It will be interesting to determine whether mutations that affect the general structure and function of the ribosome tunnel also affect the activities of these specific nascent peptides and cofactors. From the medical perspective, understanding how nascent peptides regulate ribosome activity in bacteria could provide useful insights for developing new antibiotics. At a minimum, elucidating the interactions responsible for ribosome regulation by nascent peptides should lead to more complete and dynamic models of ribosome action.

**References**

1. V. Ramakrishnan, *Cell* **108**, 557 (2002).
2. F. Gong, C. Yanofsky, *Science* **297**, 1864 (2002).
3. A. P. Geballe, M. S. Sachs, in *Translational Control of Gene Expression*, N. Sonenberg, J. W. B. Hershey, M. B. Mathews, Eds. (Cold Spring Harbor Laboratory, Cold Spring Harbor, NY, 2000), pp. 595–614.
4. D. R. Morris, A. P. Geballe, *Mol. Cell. Biol.* **20**, 8635 (2000).
5. T. Tenson, M. Ehrenberg, *Cell* **108**, 591 (2002).
6. P. S. Lovett, E. J. Rogers, *Microbiol. Rev.* **60**, 366 (1996).
7. I. S. Gabashvili *et al.*, *Mol. Cell* **8**, 181 (2001).
8. P. Nissen, J. Hansen, N. Ban, P. B. Moore, T. A. Steitz, *Science* **289**, 920 (2000).
9. R. A. Milligan, P. N. Unwin, *Nature* **319**, 693 (1986).
10. H. Nakatogawa, K. Ito, *Cell* **108**, 629 (2002).

PERSPECTIVES: QUANTUM OPTICS

# Quantum Logic with Light, Glass, and Mirrors

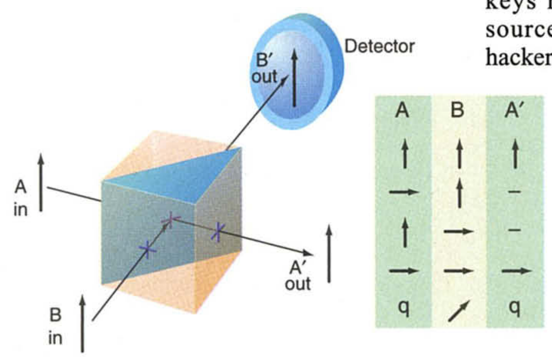
Andrew Shields

Recent progress in quantum optics suggests that quantum computers may one day be built based on single photons routed through a circuit of simple optical elements: mirrors and small bits of glass. Such circuitry would revolutionize information technology, allowing fast solution of some of the most difficult computational problems and enhancing ultrasecure communication systems.

Today's computers process information in binary format, as a sequence of **0**'s and **1**'s. With single quanta, information can be encoded not only in pure **0**'s and **1**'s, but also in states that are a mixture of **0** and **1**. These superposition states have some probability of being **0** and some of being **1**. Furthermore, the superposition increases with the number of qubits, so that a system with $n$ qubits can be in $2^n$ states simultaneously.

Quantum computers perform each operation on all $2^n$ at the same time. The resulting massive parallelism can speed up the solution of otherwise intractable problems. Although only a handful of quantum algorithms have been discovered so far, they include important mathematical problems, such as finding the prime factors of large numbers, the Achilles heel of classical cryptography (*1*, *2*).

Proposals for quantum logic hardware are based on single different quantum systems: single electron charges, electron spins, electrons in atoms or ions, photons, magnetic flux, and nuclear spins in solids and molecules (*1*, *2*). Photons have the advantage in that they interact only weakly with their environment, allowing many operations on a single photon before scattering scrambles its quantum information. This inertness also makes photons the natural choice for transmitting quantum information between processors.




**The quantum parity check gate.** This gate transfers the input qubit A to the output qubit A′ if its value is the same as that of input qubit B. If both inputs are **1** (vertically polarized photons), both will be reflected at the beam-splitter. If both are **0** (horizontally polarized), both will be transmitted. In either case, a single count in the detector means that the gate has transferred the value of A to A′. If the two input polarizations differ, either both or neither of the photons is registered in the detector, and the gate fails. The gate also works when the inputs are in superposition states (*6*).

Single-photon communication is the basis for quantum cryptography, a technique for achieving authentication and confidentiality on fiber and free space optical links (*1*, *2*). Unlike every other known method, quantum cryptography can guarantee the secrecy of encryption keys regardless of the computing resources, fancy gadgetry, or guile of a hacker. Quantum cryptography may soon secure optical links between different sites of banks or large corporations across a metropolitan area. Thus the first applications for quantum logic are very likely to be in such photonic systems.

Any measurable property of the photon can store quantum information. Many experiments choose the linear polarization (or spin) of the photon, which corresponds to the direction of its electric-field vector. For example, we could associate a horizontally polarized photon with **0** and a vertically polarized one with **1**. Because the polarization can point in any direction in the horizontal or vertical plane, a polarized photon can encode any superposition of **0** and **1**.

We can measure the linear polarization of a photon with a polarizing beam-splitter cube (*3*), which reflects all vertically polarized photons and transmits horizontal ones.

Manipulating the quantum information of a single photon is also straightforward; a thin quartz plate can rotate the photon polarization by any arbitrary angle. However, causing two photons to interact—a vital ingredient for quantum logic—is more difficult to achieve. Few materials are sufficiently nonlinear to allow re-

The author is at Toshiba Research Europe Ltd., 260 Cambridge Science Park, Milton Road, Cambridge CB4 0WE, UK. E-mail: andrew.shields@crl.toshiba.co.uk

CREDIT: PRESTON MORRIGHAN/SCIENCE

versible interaction of two photons with high efficiency (*4*). Most physicists believed that photons would therefore not be useful for quantum computation.

In the past few years, researchers have found a different approach that uses only linear optical elements, such as beamsplitters and polarization rotators. Single photons traveling through these simple optical elements can give the desired logical output, but they do so only sometimes. One might think that this is not very useful. After all, a pocket calculator that gives the correct answer just part of the time would be a liability. However, what if our calculator also had a flashing green light to tell us when it had the right answer?

The trick is to postselect the successful operations based on the output of additional single-photon detectors after feeding in additional single photons to the optical circuit (*5*, *6*). For this to work, it is important that these detectors do not give any information about the output state of the gate, because this would destroy the quantum information. With cleverly designed optical circuitry, the photon detectors will fire only if the logic operation is successful, in which case the optical path switches to feed the output of the gate into the next stage of the computation. Knill *et al.* showed that by using quantum teleportation, the probability of success of the combined logic circuit could reach nearly 100% (*5*).

Pittman *et al.* recently reported (*7*) the successful operation of a pair of simple photonic quantum logic gates: the quantum parity check (see the figure) and the destructive CNOT gate, which flips the target qubit if and only if the control qubit is equal to **1**. The latter is particularly important because it requires quantum interference between the two photons. The authors show successful operation for **0** or **1** input states, with an average error rate of 17%. They also claim flipping of a target qubit that is in a superposition of **0** and **1**.

These results demonstrate that postselection can introduce the nonlinearity required for photon logic. However, as Pittman *et al.* point out, the gates are of limited use for quantum logic as they destroy the control qubit. The next step is to combine these gates with ancillary single photons or entangled photon pairs to form a nondestructive CNOT gate, which is a potential building block for a quantum computer.

We may soon be able to pack more information onto each photon. In addition to the spin discussed earlier, photons also possess an orbital angular momentum (OAM), which is associated with the azimuthal phase of the electric field. Unlike polarization, there are an infinite number of orthogonal OAM states for each photon, raising the possibility of encoding a superposition of more than two states on a single photon. These "quNits" could improve the efficiency of quantum-computing schemes, extend the length of quantum cryptography systems (*8*, *9*), and facilitate new networking protocols involving more than two users (*10*).

Mair *et al.* have already demonstrated entanglement between the OAM states of two photons (*11*). However, the lack of a device for sorting the OAM of a single photon has hampered multi-qubit encoding. Leach *et al.* have recently shown how this can be done using an interferometric technique (*12*). At the heart of their interferometer is another simple glass element called a Dove prism, which rotates the electric-field profile of the photon. By rotating the field profile in one arm of the interferometer by 180° relative to the path through the other arm, the authors could sort photons with even and odd values of their OAM. After cascading a number of these interferometers together, they could distinguish several OAM states.

Many formidable technological challenges remain before photonic logic is ready to use. Researchers will have to perfect nondestructive gates with much lower error rates than reported to date. They will have to integrate these gates with practical sources of single photons (*13*) with close to 100% efficiency. Photon-detector technology will also have to be improved to allow almost certain detection, as well as distinguishing the photon number. We are far from realizing such components, but recent advances give good reason for optimism.

**References**


1. *Quantum Computation and Quantum Information Theory*, C .Macchiavello, G. Palma, A. Zeilinger, Eds. (World Scientific, London, 2000).
2. D. Boumeester *et al.*, *The Physics of Quantum Information* (Springer, Berlin, 2000).
3. This very common optical element consists of two back-to-back right-angle prisms in which the hypotenuse of one has a polarization-sensitive coating.
4. K. J. Resch *et al.*, *Phys. Rev. Lett.* **89**, 037904 (2002).
5. E. Knill *et al.*, *Nature* **409**, 46 (2001).
6. M. Koashi *et al.*, *Phys. Rev. A* **63**, 030301 (2001).
7. T. B. Pittman *et al.*, *Phys. Rev. Lett.* **88**, 257902 (2002).
8. D. Bruss, C. Macchiavello, *Phys. Rev. Lett.* **88**, 127901 (2002).
9. N. J. Cerf *et al.*, *Phys. Rev. Lett.* **88**, 127902 (2002).
10. M. Fitzi *et al.*, *Phys. Rev. Lett.* **87**, 217901 (2001).
11. A. Mair *et al.*, *Nature* **412**, 313 (2001).
12. J. Leach *et al.*, *Phys. Rev. Lett.* **88**, 257901 (2002).
13. Z. Yuan *et al.*, *Science* **295**, 103 (2002).


PERSPECTIVES: CANCER

# *BRCA2* Enters the Fray

**John H. Wilson and Stephen J. Elledge**

About half of all familial cases of breast and ovarian cancer are caused by mutations in the *BRCA1* and *BRCA2* genes. Heterozygous germline mutations in these genes confer a 30 to 70% lifetime risk of breast or ovarian cancer on affected individuals. Tumors derived from these patients invariably display inactivation of both copies (loss of heterozygosity) of either *BRCA1* or *BRCA2*. Despite numerous studies, it is still not clear what the BRCA proteins do in the cell, and their amino acid sequences hold few clues. Hints suggesting that BRCA1 and BRCA2 are involved in DNA repair have been gleaned the old-fashioned way—through cell biology, biochemistry, and inspired guesswork. On page 1837 of this issue, Yang *et al.* (*1*) place these hints on solid ground by providing structural and biochemical evidence that BRCA2 is directly involved in the repair of DNA double-strand breaks.

The initial link between the *BRCA* genes and DNA repair derives from the key observation that BRCA1 displays a characteristic nuclear dot pattern during S phase of the cell cycle after immunostaining (*2*). This pattern is similar to that observed for human RAD51, a homolog of the bacterial recombination protein RecA. RAD51 is a bona fide participant in the homologous repair of DNA double-strand breaks, a process that uses the sister chromatid as a template for repair. During S phase, BRCA1, BRCA2, and RAD51 become colocalized in nuclear dots, which then disperse after arrest of DNA synthesis. In response to ionizing radiation or cross-linked DNA, these S-phase nuclear dots disperse and reform smaller foci that contain proliferating cell nuclear antigen and are presumptive sites of DNA repair (*3*, *4*). Furthermore, coimmunoprecipitation experiments indicate that BRCA1, BRCA2, and RAD51 are physically associated (*4*–*6*). Finally, cells containing mutations in either *BRCA1* or *BRCA2* are

J. H. Wilson and S. J. Elledge are in the Verna and Marrs McLean Department of Biochemistry and Molecular Biology, and the Department of Molecular and Human Genetics, Baylor College of Medicine, Houston, TX 77030, USA. S. J. Elledge is also with the Howard Hughes Medical Institute, Baylor College of Medicine, Houston, TX 77030, USA. E-mail: selledge@bcm.tmc.edu