

FINAL FOCUS TEST
Facility, at the downstream end of the 2-mile Stanford Linear Accelerator, sits in the long, narrow white shack at center foreground. Built to study beam focusing for a future TeV linear e^+e^- collider, the FFTF was recently used¹ to create an intense Compton-backscattered gamma beam for the study of photon-photon scattering.



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agreement with the predicted ratio of positrons to the Compton-scattered beam electrons monitored by the experiment's Čerenkov counters. Positrons are first deflected out of the electron beam by a string of magnets and then counted by an electromagnetic calorimeter. Below $\eta \approx 0.2$, the positron signal is dominated by various background effects.

Sparking the vacuum

In 1928, not long after the debut of the Dirac equation, the Swedish theorist Oskar Klein pointed out a paradox: When applied to an electron impinging on a sufficiently steep potential wall, the Dirac equation yields a reflection coefficient greater than unity.

In 1936, the positron having been discovered in the meantime, Werner Heisenberg resolved Klein's paradox in terms of spontaneous e^+e^- pair creation in an ultrastrong electric field: If the electric field strength exceeds a critical value

$$E_c \equiv m_e c^2 / e \lambda_e = 1.3 \times 10^{16} \text{ V/cm}$$

(where $\lambda_e \equiv \hbar / m_e c = 3.9 \times 10^{-11} \text{ cm}$ is the electron Compton wavelength), the vacuum can go to a lower energy state by spontaneously creating an e^+e^- pair.

In 1951, Julian Schwinger gave this putative sparking of the vacuum a modern quantum-field-theoretic footing, and experimenters began to seek it out. In the 1980s, considerable attention was attracted by attempts to create a quasistatic critical field fleetingly by bringing stripped uranium and thorium ions into close proximity. Some of that attention was aroused by evidence—that seems in the meantime to have evaporated²—for the creation of an exotic neutral particle in the ultrastrong electric field between the colliding nuclei. Weighing only about $3m_e$, this putative particle was thought to decay into an e^+e^- pair. (See *PHYSICS TODAY*, November 1985, page 17.) Even if this peculiar object did exist, the recent SLAC experiment could not

have seen it, because this experiment was not able to measure the invariant masses of e^+e^- pairs.

In a static critical electric field, energy and momentum are conserved simply by having the electron and positron created with equal and opposite momenta. But in a plane-wave laser field, the peripheral participation of a charged particle is needed to balance momentum. In the SLAC experiment, the laser field, for all its intensity, still falls far short of E_c . But things look much better in the reference frame of the highly relativistic electron beam. A 46.6 GeV electron sees the laboratory electric field augmented by a factor $2\gamma = 1.8 \times 10^5$, where the Lorentz factor γ is 46.6 GeV/ $m_e c^2$. Thus the electrons see an rms laser field close to half of E_c , so that the SLAC experiment can probe a largely unexplored regime of QED.

"I believe that our pair-production data can be interpreted either as light-by-light scattering or, alternatively, as the spontaneous breakdown of the vacuum, as seen in the rest frame of the electron whose Compton collision creates the GeV photon," Melissinos told us. Even though the beam electrons see the wavelength of the laser beam foreshortened by the Lorentz factor γ , one can nonetheless approximate the laser field in that frame as static, because the fore-

shortened wavelength is still longer than the electron Compton wavelength.

For a static field near the critical value, QED predicts that the rate of spontaneous e^+e^- pair creation should be proportional to $e^{-\pi/Y}$, where the Lorentz-invariant parameter Y is E^*/E_c and E^* is the electric field strength seen in the appropriate Lorentz frame. But because the role of the high-energy electron here is so peripheral, it is not entirely clear whether, in this case, it should be the rest frame of the electron beam or of an imagined electron with the same energy as the gamma ray. In either case, the group found that their positron production data obeyed the predicted exponential dependence of vacuum sparking on the electric field strength reasonably well.³

Future colliders

"Aside from testing QED at very high field strengths," McDonald told us, "we're also exploring the technology that will be required for the gamma-gamma colliders that particle physicists are thinking about building. Backscattered gamma beams have been around since the 1960s, but ours is the first really intense one. It's an existence proof for the requisite high-efficiency transfer of energy from TeV electrons to photons." To which David Burke, head of the collaboration's SLAC contingent, adds that "it's also the first time we've been able to look at anything like the environment we'd have to face at the focus of a TeV electron-positron collider."

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References

1. D. L. Burke *et al.*, *Phys. Rev. Lett.* **79**, 1626 (1997).
2. R. Ganz *et al.*, *Phys. Lett. B* **389**, 4 (1996).
3. K. McDonald, in *Proc. 1997 SLAC Summer Institute on Particle Phys.*, Stanford U., to be published. T. Kotseroglou, in *Proc. 6th Internat. Workshop on Laser Phys.*, Prague, Aug. 1997, to be published.

Quantum Teleportation Channels Opened in Rome and Innsbruck

If you've heard the reports that teleportation has been achieved, and you're anxious about the implications for investments in the transportation sector, you can relax and instead look to physics futures for the payoff. Quantum teleportation as it currently exists involves the delicate dismantlement of an individual photon's quantum state and its reconstruction about a meter away. Although that may sound less exciting than the transport of starship

Two experiments, using different optical schemes, have transmitted quantum states across a tabletop by means of classical messages and Einstein-Podolsky-Rosen entanglement. Applications will include new tests of the fundamentals of quantum mechanics and quantum computation.

captains from orbit to planet surface, it should lead to new tests of the non-

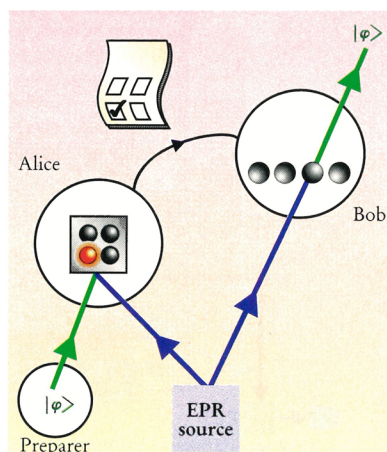
existence of what Albert Einstein, Boris Podolsky and Nathan Rosen called local “elements of reality.”

The quantum teleportation experiments have been performed by two groups. A two-photon procedure¹ that can in principle achieve a 100% success rate was carried out at the University of Rome (“La Sapienza”) in Italy by Francesco De Martini, Danilo Boschi, Salvatore Branca, Lucien Hardy (now at the University of Oxford) and Sandu Popescu (University of Cambridge and the Hewlett-Packard Laboratories in Bristol, England). A four-photon design² that pioneers a difficult interference measurement was used at Innsbruck University in Austria by Dik Bouwmeester, Jian-Wei Pan, Klaus Mattle, Manfred Eibl, Harald Weinfurter and Anton Zeilinger.

Quantum teleportation theory, an application of standard quantum mechanics, was created in 1992 by Charles H. Bennett, Gilles Brassard, Claude Crépeau, Richard Jozsa, Asher Peres and William K. Wootters.³ Neither experiment completely fulfilled the scheme outlined in that proposal, and some argue that one or the other experiment is not true teleportation, but Bennett says that “it is fair to call either of these experiments teleportation” because each experiment “includes the essential idea.” Alain Aspect (Institute of Optics in Orsay, France) believes that “the most important lesson of these experiments is that they allow us to see another amazing feature of quantum mechanics, and to realize that nature follows quantum mechanical predictions even when these predictions seem to be crazy.”

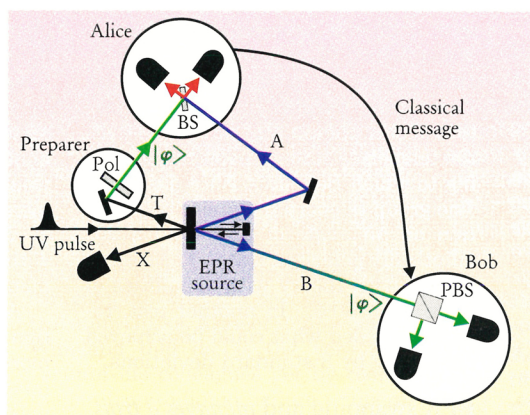
Theoretical ideal

As expressed in the original theoretical proposal, quantum teleportation works as follows: A preparer gives Alice a particle whose quantum state $|\varphi\rangle$ is to be sent to Bob. The state $|\varphi\rangle$ is arbitrary and unknown to Alice, so she cannot determine it by a measurement and send that data to Bob classically. Instead, using the same ingredient as the Einstein-Podolsky-Rosen (EPR) experiment, she and Bob each have one particle from an entangled pair of particles. Alice carries out a joint Bell-state measurement on the teleported particle and her EPR particle, which projects the two-particle system into one of four orthogonal states called Bell states. (See the article by Bennett, *PHYSICS TODAY*, October 1995, page 24.) The result of



IN IDEAL QUANTUM TELEPORTATION, Alice and Bob each have one of a pair of Einstein-Podolsky-Rosen-entangled particles (purple). Alice performs a joint Bell-state measurement on her EPR particle and the particle whose state $|\varphi\rangle$ is to be teleported (green). When Bob learns, by way of classical communication, which of four possible results Alice obtained, it tells him which of four unitary transformations to apply to his EPR particle to recreate the state $|\varphi\rangle$.

Alice's measurement is twofold. First, it supplies her with two random bits of classical information—which one of the four states she observed. Second, the quantum state reduction induced by the measurement obliterates the



INNSBRUCK EXPERIMENT: An ultraviolet pulse (UV) passes through a nonlinear crystal twice, producing an entangled photon pair moving to the right (purple) and a pair (T, X) moving to the left. The state $|\varphi\rangle$ to be teleported is prepared by setting the polarization of photon T. Alice combines that photon with her EPR photon (A) at a beam splitter (BS). When both of her detectors fire simultaneously, it indicates observation of a photon pair in the Bell state $|\Psi^-\rangle$, which implies Bob's photon is now in state $|\varphi\rangle$. Bob analyzes his photon with a polarizing beam splitter (PBS). Detection of photon X confirms that photon T was sent to Alice. This eliminates spurious coincidences caused by, for example, two photon pairs traveling along paths A and B at the same time.

state $|\varphi\rangle$ in her hands and changes the state of Bob's EPR particle to a copy of $|\varphi\rangle$, up to a local transformation that depends on which of the four outcomes Alice obtained. When Alice tells Bob which result she obtained, he knows which transformation to apply (for example, a 180° rotation of its spin) to make his particle's state identical to the original. (See the figure at left.)

The transmission of $|\varphi\rangle$ from Alice to Bob has thus taken place through two channels. The message from Alice to Bob about the measurement result involves ordinary classical information. However, the quantum information needed to reconstruct the unknown quantum state $|\varphi\rangle$ has traveled instantaneously by means of the EPR pair. The Rome and Innsbruck experiments both succeeded in this core process, the transmission of quantum information through a combination of classical communication and EPR correlations. (The need for classical communication makes the overall process obey the universal speed limit: the speed of light.)

Photons forget their past

In practice, creating entangled pairs of particles is a very difficult problem, except in the case of photons. Parametric down conversion, a workhorse in the field of quantum optics, produces entangled photon pairs when a photon passing through a nonlinear crystal is converted into two photons. Both the Innsbruck and Rome experiments used this technique to generate their entangled states.

Having produced one's entangled photons, the remaining severe difficulty is performing the complete Bell measurement on a pair of photons. “The conditions for doing such a measurement,” Zeilinger told us, “were not at all evident to anyone at the time of Bennett *et al.*'s teleportation proposal. It took us a long time to identify the necessary physics. What it amounts to is a quantum eraser procedure where the two photons are measured in such a way that all information about their individual identity is erased. They forget, so to speak, from which source each one came.” (See the article by Daniel Greenberger, Michael Horne and Zeilinger, *PHYSICS TODAY*, August 1993, page 22.) Zeilinger credits Marek Żukowski (University of Gdańsk in Poland) with crucial help in understanding how these conditions could be achieved by producing the photons in very short pulses and passing them

through filters to make their coherence times longer than the pulses. In addition to demonstrating quantum teleportation, the Innsbruck experiment amounts to observation of second-order interference between photons from two different sources. Previous experiments have observed interference between two distinct photons, but with both coming from the same source.

Nonetheless, the Innsbruck Alice did not perform a complete Bell measurement. Instead, she distinguished only one of the Bell states, $|\Psi^-\rangle$, from the other three. (See the lower figure on page 19 for a description of the Innsbruck experiment.) Thus, teleportation could be achieved at best only 25% of the time—on those occasions when Alice happened to detect $|\Psi^-\rangle$. The classical message in this experiment consisted of Alice telling Bob on which occasions she saw $|\Psi^-\rangle$. In the other 75% of the runs, the state $|\varphi\rangle$ was lost. Zeilinger says his group expects soon to implement a scheme that will identify two of the four Bell states, but identifying all four states of the group's two-photon system "would require a quantum gate that does not exist yet."

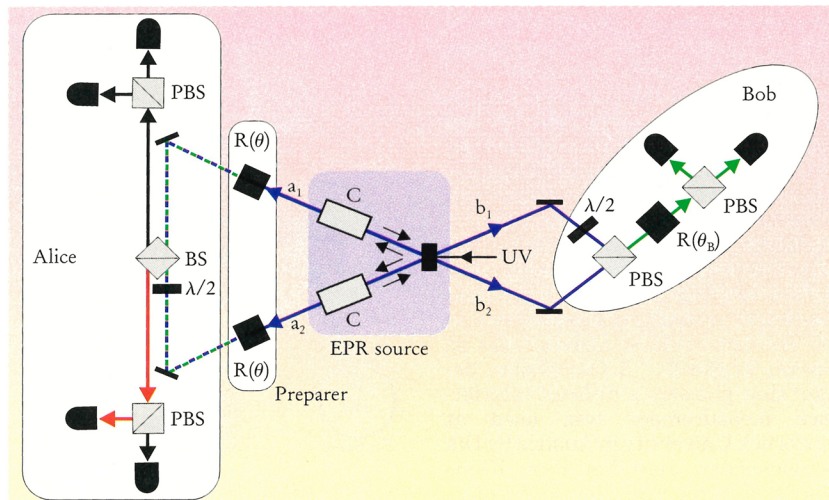
The Innsbruck group observed the expected signal of teleportation for five states $|\varphi\rangle$: plane polarization at 0° , 90° and $\pm 45^\circ$, and circular polarization. They achieved visibilities of up to 70%. (A perfect system would achieve 100%; an ideal but wholly classical system could achieve visibilities of up to 50%.)

A photon remembers two states

The problem of performing a joint Bell measurement on two particles can be sidestepped, as was pointed out in 1994 by Popescu.⁴ The trick is to encode the two quantum states to be measured by Alice on different degrees of freedom of a single particle. For example, one state could be encoded in a photon's polarization, the other in which of two paths the photon follows. This approach transforms a singularly difficult interference measurement into a routine process: detection of a photon of a specific polarization at a specific location. By implementing this technique, the Rome group succeeded in performing a complete Bell measurement, with Alice's four detectors corresponding to the four possible states.

This simplification does have its drawbacks, however. In the Rome experiment, the preparer could not give Alice a photon in an arbitrary state to be teleported; instead the preparer selected a pure quantum state (a polarization) and inscribed it directly on the polarization of Alice's EPR photon. (For a description of the Rome experiment, see the figure above.)

The teleportation presented Bob



ROME EXPERIMENT: An ultraviolet pulse (UV) passing through a nonlinear crystal produces a pair of photons entangled in polarization and traveling to the left. A calcite crystal/mirror combination (C) in each path separates the horizontal and vertical polarization component of each photon. The result is one vertically polarized photon $|a\rangle$ traveling to the left (in a superposition of paths a_1 and a_2) and one horizontally polarized photon $|b\rangle$ traveling to the right (on paths b_1 and b_2). The photons' paths are entangled: $|a_1\rangle|b_1\rangle + |a_2\rangle|b_2\rangle$. The preparer inscribes the teleported state $|\varphi\rangle$ on the polarization of photon $|a\rangle$ by means of two identical polarization rotators $R(\theta)$ and (for elliptical polarizations) quarter-wave plates (not shown). Alice performs a complete Bell-state measurement on photon $|a\rangle$'s two degrees of freedom—its polarization and its path. One of her four detectors sees the photon and thus singles out a specific Bell state. Bob converts his photon from a path superposition to a polarization state by means of a half-wave plate and a polarizing beam splitter (PBS). He could then recover the polarization state $|\varphi\rangle$ by applying one of four transformations to his photon, according to which of Alice's four detectors fired. Instead, he verifies that his photon's polarization is appropriately correlated with the teleported state $|\varphi\rangle$ and Alice's measurement result.

with a photon superposed across two paths, which he converted to a polarization state on a single path. The Rome group verified that the polarization of this photon was correlated with the teleported state as expected according to which Bell state Alice observed. The group teleported a linear polarization on an angle of 22.5° and a 20° elliptically polarized state. The results agreed with theory with visibilities of more than 80%. In another test, results exceeded what could be achieved classically by 8 standard deviations.

EPR swapping and *ménages à trois*

Among the most intriguing applications of the techniques pioneered in these two experiments will be new tests of quantum mechanics. One example is "entanglement swapping," which occurs if one gives Alice one member of an entangled pair as the teleported particle: Teleporting this state transfers the *entanglement* to Bob's particle. That is, his particle becomes entangled with the teleported state's partner, even though the two particles have neither interacted nor shared a common past. A test of Bell's theorem using entan-

glement swapping could test nonlocality with a pair of particles that have never interacted directly. This would be really new, Aspect says: "It would certainly help us to further understand nonlocality." Entanglement swapping would occur in the Innsbruck experiment simply by not polarizing photon T. Photon X would become entangled with photon B when Alice's measurement of T and A succeeded.

A related possibility is the generation of entanglement among three or more separated particles. Such promiscuous states would allow all-or-nothing tests that would, with no ambiguity, either contradict quantum mechanics or rule out the existence of local elements of reality. (See the August 1993 PHYSICS TODAY article by Greenberger, Horne and Zeilinger.)

Teleportation can also be applied in a number of ways for quantum computation. De Martini suggests that quantum logic gates might be constructed using Popescu's trick of putting two quantum bits on a single particle. Teleportation could also be used to move quantum information from one processor to another. Aspect says that "the

possibility of transferring a quantum state from a fragile system to a more robust one, or from a continually flying photon to an atom or ion at rest, may turn out to be extremely important."

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References

1. D. Boschi, S. Branca, F. De Martini, L.

- Hardy, S. Popescu, to appear in *Phys. Rev. Lett.* **80** (1998).
2. D. Bouwmeester, J.-W. Pan, K. Mattle, M. Eibl, H. Weinfurter, A. Zeilinger, *Nature* **390**, 575 (1997).
3. C. H. Bennett, G. Brassard, C. Crepeau, R. Jozsa, A. Peres, W. Wootters, *Phys. Rev. Lett.* **70**, 1895 (1993).
4. S. Popescu, preprint quant-ph/9501020, available at <http://xxx.lanl.gov/> (1995).

An Ion Clock Reaches the Accuracy of the Best Atomic Fountain

The most accurate primary frequency standards in the world today reside in the national standards laboratories of several countries: They are an atomic-fountain clock at the Paris Observatory's Bureau National de Métrologie—Laboratoire Primaire de Temps et Fréquences and two atomic-beam clocks, one run by the US National Institute of Standards and Technology (NIST) in Boulder, Colorado, and another by the German Federal Institute of Physics and Metrology in Braunschweig.

The instruments in Paris and Boulder determine the frequency of a ground-state hyperfine microwave transition in a cesium atom to an accuracy of a few parts in 10^{15} . Now an ion clock is taking its place alongside these two: A group at the NIST facility in Boulder has operated a clock based on cooled and trapped mercury ions that has both a stability and an accuracy comparable to the atomic fountain in Paris and the atomic beam in Boulder.¹ In particular, the NIST researchers report that their ion clock has an uncertainty from systematic effects of 3.4 parts in 10^{15} . They have found that the fractional frequency stability—a measure of the fluctuations in frequency measurements—is $3.3 \times 10^{-13} \times t^{-0.5}$. (Contrary to the misleading name of this stability parameter, the lower its value, the more stable the clock.) The frequency stability is in the same league as those of the reigning time standards.

Christophe Salomon of the Ecole Normale Supérieure in Paris, who is working with Andre Clairon of the Paris Observatory to attain still greater accuracy with the atomic fountain clock, is quite pleased with the new development. "It keeps the competition between ions and neutrals alive," he said, adding that "both [the atomic fountain and the trapped ion] still have a large potential for improvement."

Ion clocks

The ideal basis for a highly accurate clock might be a single atom at rest in

By cooling mercury ions and confining the ions to the one line in their linear ion trap where the RF field is exactly zero, researchers have minimized the jiggling and heating that have confounded many attempts to achieve precise determinations of frequency.

a field-free region of space. The linewidth of its atomic transition would remain fixed and narrow, not broadened by Doppler shifts or perturbed by interactions with the environment. An ion trap is close to this ideal, and researchers in the 1980s did indeed measure an exceptionally narrow optical transition in a single trapped ion. (See *PHYSICS TODAY*, September 1989, page 17.) But further progress at that time was hindered by instability of available lasers and by the loss of ions from the trap, which shortened the time available for measurement.

Several groups around the world have since tackled these problems in an effort to improve the performance of an ion clock. Now Dana Berkeland, John D. Miller, James Bergquist, Wayne Itano and David Wineland at the NIST facility in Boulder have succeeded in operating an ion clock that can compete with the best of the neutral atom clocks. A major improvement, Wineland told us, is the very good vacuum his colleagues get by cooling the ion trap to liquid helium temperatures. At room temperature, the mercury ions collide with atoms in the background gas (primarily mercury atoms) and are subsequently lost to the trap (through chemical reactions). The cryogenic cooling has eliminated these ion losses. Berkeland and her colleagues also developed very stable ultraviolet lasers to cool and detect the mercury ions.

With a better vacuum and improved lasers, one remaining problem was the motion of the ions due to the RF field that is used to confine the ions to the trap. The ions oscillate in response to

the field, and that micromotion can heat the ions. The researchers of course could not get rid of the RF field, which is needed for trapping, but they were able to minimize its impact on the ions: They used a linear ion trap, so that the ions, in cooling, formed a "linear crystal," a row of ions aligned with a nodal line of the trap, where the RF field is zero.

Other groups have used the trick of confining clouds of ions near a nodal line of a linear trap to make more stable ion clocks,^{2,3} in some cases with a frequency stability as much as ten times higher than that recently reported by Berkeland and company. However, because the ions were not laser cooled or exactly confined to a nodal line, the systematic errors in these devices are over ten times higher than those in the current NIST ion clock.

The ion-clock group at NIST still sees lots of room for improvement. The remaining big terms in the uncertainty from systematic effects are the Zeeman shifts caused by both static and AC magnetic fields. The static fields can be mitigated by adding more shielding against external fields. The AC magnetic fields stem from small currents that run in the RF electrodes in the trap. Bergquist told us that the NIST researchers plan to operate at different RF frequencies and different power levels, first to minimize the AC field shift and then to correct for this shift.

Bergquist also mentioned the group's plans to trap more than the seven atoms on which their current results are based. The stability varies inversely as the square root of the number of ions, so the more ions, the more stable the clock. The NIST experimenters can put more ions into their trap and still keep the RF power low if they build a smaller mercury ion trap.

Large measurement times

In any atomic clock, the operator excites the ions or atoms with radiation close to the intended clock transition and counts the number of atoms that are excited by the signal. The RF frequency can be adjusted until the number of excited atoms is maximized; the applied frequency should then be on resonance. The actual procedure is a bit more complicated. Researchers use the method of separated oscillatory fields devised by Norman Ramsey in 1949 to narrow the linewidth of the measured resonance. This method dictates that the pulse of exciting radiation be given in two bursts; between those bursts, the atom evolves freely. The longer the time between pulses, the narrower the resonance and the