Gamma Rays Create Matter Just by Plowing into Laser Light

When a beam of 50-GeV electrons collides head on with a terawatt laser pulse focused down to a few microns, extraordinary things can happen: Almost every electron plowing through the very dense laser field at the focus kicks a low-energy photon up to multi-GeV gamma-ray energy, and lots of these "Compton-backscattered" gammas then create electron–positron pairs when they subsequently collide with laser photons coming toward them.

Quantum electrodynamics predicts that photons scattering off nothing but light should create electron–positron pairs. But only now has this inelastic light–light scattering been seen in the laboratory.

Such an experiment, recently carried out at the Stanford Linear Accelerator Center by a SLAC, Princeton, University of Rochester, University of Tennessee collaboration, was described by the group as "the first laboratory evidence for inelastic light-by-light scattering involving only real [as distinguished from virtual] photons."[1] Electron–positron pairs produced by gamma rays interacting with charged particles through the mediation of virtual photons are commonplace, and pair production by real photon collisions has been invoked to explain various astrophysical observations. But the SLAC experiment was the first direct observation of material particles produced by nothing but photons.

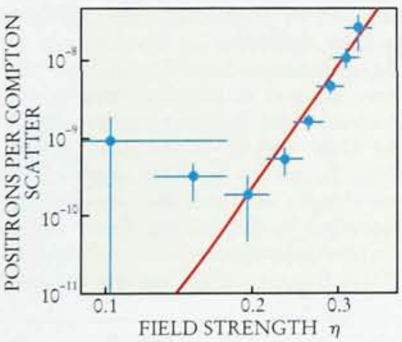
This e^+e^- pair creation can also be thought of as the "sparking of the vacuum," an exotic prediction of quantum electrodynamics at extremely high electric field intensities. QED is, by far, the most precisely tested of all theories in physics. But the new terawatt laser technology, in concert with a tightly focused high-energy electron beam, now makes it possible to test QED at electromagnetic field strengths far beyond the range of traditional experiments.

The experiment

The collaboration, whose spokesmen are Kirk McDonald (Princeton) and Adrian Melissinos (Rochester), carried out the experiment at SLAC's Final Focus Test Facility. The FFTF, which sits at the downstream end of the two-mile-long linear accelerator, can focus the 50 GeV electron beam down to 60 nm, primarily for studies related to the TeV linear collider foreseen for the next generation. (See PHYSICS TODAY, November 1997, page 21.) But in this experiment it focused a 46.6 GeV beam down to a spot 25 μm across.

Almost head-on into this tightly focused, pulsed electron beam, the group fired its even more tightly focused picosecond laser pulses of green (527 nm) light, with a peak power density of 10^{18} W/cm^2. That corresponds to an incredible density of almost 10^{28} optical photons per cubic centimeter, or an rms electric field strength exceeding 10^{10} V/cm. The neodyium:glass laser that produced those prodigious terawatt pulses was developed by the University of Rochester's Laboratory for Laser Energetics. (See PHYSICS TODAY, January, page 22.)

QED predicts that, above the center-of-mass threshold energy ($2m_e c^2 = 1.02$ MeV) for creating e^+e^- pairs, the cross section for pair production by photon–photon collision should be on the order of the square of the classical electron radius (2.8×10^{-13} cm). That's quite large; it's comparable to the hadronic cross section of the proton.



POSITRONS CREATED by gamma rays traversing a terawatt laser-pulse focus whose electromagnetic field strength is given by the parameter η. The gammas are produced by Compton backscattering of the same laser beam off a 46.6 GeV pulsed electron beam at SLAC. The number of observed positrons is normalized to the number of Compton-scattered beam electrons detected in the same pulse. The red line is the quantum-electrodynamic prediction for e^+e^- pair production. Below $\eta \approx 0.2$ the data are dominated by background effects. (Adapted from ref. 1)

But the SLAC experiment was below threshold. The highest energy a 527 nm (2.35 eV) photon can attain by backscattering off a 46.6 GeV electron is only 29.2 GeV, well short of the minimum 111 GeV that a high-energy photon (ϕ_γ) would require to make an e^+e^- pair by colliding head-on with a single 2.35 eV laser photon (ϕ_0).

Therefore the pair production could only proceed by the multiphoton reaction

$$\phi_\gamma + n\phi_0 \rightarrow e^+ + e^-, \qquad (1)$$

where n, the number of low-energy photons simultaneously absorbed by the gamma ray, must be at least 4.

Multiphoton nonlinearity

The probability for such a multiphoton reaction must obviously be a highly nonlinear function of the photon density or, equivalently, the laser electric field strength E. A useful Lorentz-invariant measure of the field strength is the dimensionless parameter η, given in the laboratory frame by $eE_{rms}/m_e\omega_0 c$, where ω_0 is the frequency of the laser field. Multiphoton reactions don't become prominent until η approaches unity. For a given n in reaction 1, QED predicts that the rate of e^+e^- pair production grows with laser photon density like η^{2n}. That's quite plausible, because the photon density is proportional to η^2.

And it's just about what the collaboration found when they varied the laser intensity and measured positron yield as a function of η. The experimental data plotted in the figure at left exhibit a power-law growth above $\eta \approx 0.2$ corresponding to an n of about 5.1. The number of photons involved varies from event to event, but detailed QED simulations indicate that an average of 4.7 photons are absorbed from the laser field in reaction 1. The QED predicted line in the figure also has to take account of the prerequisite Compton-backscattering event that creates the high-energy gamma ray; this backscattering can also involve more than one laser photon.

The good fit of the data to QED is all the more impressive when one notes that the absolute normalization, not just the power-law slope, is in good

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 used[1] 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

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

(where $\lambda_e \equiv \hbar / m_e c = 3.9 \times 10^{-11}$ 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 evaporated[2]—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 electons 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 foreshortened 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 $e^{-\pi/\Upsilon}$, where the Lorentz-invariant parameter Υ 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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Quantum Teleportation Channels Opened in Rome and Innsbruck

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.

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