Positron Production
by Laser Light

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Seminar at U. Maryland
Sonoluminescence

In 1850, the Navier-Stokes equation was the “theory of everything”, but it doesn’t predict sonoluminescence. [Erber]

[Sonoluminescence is what makes nitroglycerine explode.]

• Preparata (1998): QED theory of water vapor predicts emission of light when water vapor condenses at density near 1 g/cm$^3$.

• Schwinger (1992): a bubble is an electromagnetic cavity; an imploding bubble will radiate away the changing, trapped zero-point energy.

• Liberati (1998): Imploding bubble $\Rightarrow$ rapidly changing index $\Rightarrow$ associated radiation.

This relates to an earlier idea:

• Yablonovitch (1989): An accelerating boundary across which the index of refraction changes is a possible realization of the Hawking-Unruh effect, leading to conversion of QED vacuum fluctuations into real photons.
The Hawking-Unruh Effect

Hawking (1974): An observer outside a black hole experiences a bath of thermal radiation of temperature \( T = \frac{\hbar g}{2\pi c k} \), where \( g \) is the local acceleration due to gravity.

Unruh (1976): According to the equivalence principle an accelerated observer in a gravity-free region should also experience a thermal bath with: \( T = \frac{\hbar a}{2\pi c k} \), where \( a \) is the acceleration of the observer as measured in his instantaneous rest frame.

Unruh Radiation (?)

Suppose the observer is an electron, accelerated by a field $E$.

Thomson scattering off photons in the apparent thermal bath implies a radiation rate:

$$\frac{dU_{\text{Unruh}}}{dt} = \text{thermal energy flux} \times \text{Thomson cross section} = \frac{\hbar r_e^2 a^4}{90\pi c^6}.\]

[Stefan-Boltzman: flux $\propto T^4$, Unruh: $T^4 \propto a^4$.]

This equals the Larmor radiation rate, $dU/dt = 2e^2a^2/3c^3$, when the acceleration $a = eE/m$ is about $10^{31}$ g, i.e., when

$$E = \sqrt{\frac{60\pi}{\alpha}} \left(\frac{m^2c^3}{e\hbar}\right) \approx 3 \times 10^{18} \text{ V/cm}.$$

Can we do the experiment?
Strong-Field QED

For high acceleration, need strong electromagnetic field.

Strongest macroscopic electromagnetic fields are in lasers.

Tabletop teraWatt lasers can be focused to $> 10^{19}$ W/cm$^2$.

⇒ Electric fields $> 100$ GeV/cm.

[Photon number density $> 10^{27}$/cm$^3$.]

(Nonperturbative) physics described by two dimensionless measures of field strength:

$$\eta = \frac{e\sqrt{\langle A_\mu A^\mu \rangle}}{mc^2} = \frac{eE_{\text{rms}}}{m\omega_0c} = \frac{eE_{\text{rms}}\lambda_0}{mc^2},$$

governs the importance of multiple photons in the initial state, and characterizes the “mass shift”: $\overline{m} = m\sqrt{1 + \eta^2}$. [Kibble, 1996]

$$\Upsilon = \sqrt{\langle (F^{\mu\nu}p_\nu)^2 \rangle} = \frac{2p_0}{mc^2} \frac{E_{\text{rms}}}{E_{\text{crit}}} = \frac{2p_0}{mc^2} \frac{\lambda_C}{\lambda_0} \eta,$$

governs the importance of “spontaneous” pair creation, where $E_{\text{crit}} = \frac{m^2c^3}{e\hbar} = \frac{mc^2}{e\lambda_C} = 1.3 \times 10^{16}$ V/cm.
The QED Critical Field Strength

• O. Klein (Z. Phys. 53, 157 (1929)) noted that the reflection coefficient exceeds unity when Dirac electrons hit a steep barrier (Klein’s paradox).

• F. Sauter (Z. Phys. 69, 742 (1931)) deduced that the paradox arises only in electric fields exceeding the critical strength:

\[ E_{\text{crit}} = \frac{m^2 c^3}{e \hbar} = 1.32 \times 10^{16} \text{ Volts/cm}. \]

• At the critical field, the energy gain across a Compton wavelength is the electron rest energy:

\[ eE_{\text{crit}} \cdot \frac{\hbar}{mc} = mc^2. \]

• At the critical field the vacuum ‘sparks’ into \( e^+ e^- \) pairs (Heisenberg and Euler, Z. Phys. 98, 718 (1936)).

Dimensionless measure of criticality: \( \Upsilon = \frac{E}{E_{\text{crit}}} \).
Where to Find Critical Fields

• The magnetic field at the surface of a neutron star approaches the critical field $B_{\text{crit}} = 4.4 \times 10^{13}$ Gauss.

• During heavy-ion collisions where $Z_{\text{total}} = 2Z > 1/\alpha$, the critical field can be exceeded and $e^+e^-$ production is expected.

$$E_{\text{max}} \approx \frac{2Ze}{\lambda_C^2} = 2Z\alpha E_{\text{crit}}.$$  

The line spectrum observed in positron production in heavy-ion collisions (Darmstadt) is not understood.

• Pomeranchuk (1939): The earth’s magnetic field appears to be critical strength as seen by a cosmic-ray electron with $10^{19}$ eV.

• The electric field of a bunch at a future linear collider approaches the critical field in the frame of the oncoming bunch.
Critical Fields in e-Laser Collisions

• The electric field due to a laser as seen in the rest frame of a high-energy electron is

\[ E^\star = \gamma (1 + \beta) E_{\text{lab}} \approx 2\gamma E_{\text{lab}}, \]

so

\[ \Upsilon = \frac{E^\star}{E_{\text{crit}}} = \frac{2\gamma E_{\text{lab}}}{E_{\text{crit}}} = \frac{\sqrt{(F_{\mu\nu}p^{\nu})^2}}{mc^2E_{\text{crit}}}. \]

• The critical field is achieved with a laser beam of intensity

\[ I = \frac{E_{\text{lab}}^2}{377\Omega} = \frac{E_{\text{crit}}^2}{4\gamma^2 \cdot 377}. \]

Thus for 46-GeV electrons (\( \gamma = 9 \times 10^4 \)) we can achieve \( E_{\text{crit}} \) with a focused laser intensity of \( 1.4 \times 10^{19} \) Watts/cm\(^2\)

(\( \Rightarrow E_{\text{lab}} = 7 \times 10^{10} \) Volts/cm).

• Such intensities are now attainable in table-top teraWatt (T\(^3\)) lasers in which a Joule of energy is compressed into one picosecond and focused into a few square microns.

• At these intensities the photon density is \( \sim 10^{27}/\text{cm}^3 \), and the radiation length of this ‘photon solid’ is \( \sim \lambda_0/\alpha \approx 100 \mu\text{m} \).
Another Aspect of Electrons in Strong Wave Fields

Simplest to consider a circularly polarized laser beam incident on an electron at rest. Laser field is $E$, frequency is $\omega_0$.

Classical response of electron is transverse motion in a circle with angular velocity $\omega_0$ and velocity described by

$$\frac{v_\perp}{c} = \frac{eE}{m\omega_0 c} \equiv \eta.$$

[\eta = e\sqrt{\langle A_\mu A^\mu \rangle}/mc^2 \text{ where } A_\mu \text{ is the vector potential.}]

The accelerating electron emits multipole radiation.

Rate$_n \propto \eta^{2n} \propto I^n$ for $n$th-order multipole ($\eta \lesssim 1$).

$n$th order $\Leftrightarrow$ absorption of $n$ photons before emitting a single higher-energy photon $\Leftrightarrow$ nonlinear Compton scattering.

$\Upsilon$ and $\eta$ are related by

$$\Upsilon = \frac{2\gamma E_{\text{lab}}}{E_{\text{crit}}} = \frac{2\gamma \hbar \omega_0}{mc^2} \eta \approx \eta \text{ in our experiment.}$$

$\Rightarrow$ Two classes of strong-field effects to be untangled.
The Mass Shift Effect

An electron propagating in a (periodic) wave field of strength \( \eta = eE/m\omega_0c \) takes on an effective mass

\[
\bar{m} = m\sqrt{1 + \eta^2}.
\]

Classical view: the transverse oscillations of the electron are relativistic, so it becomes ‘heavier’.

As a result the kinematic limits in nonlinear Compton scattering (and threshold for pair creation) are shifted.

Pedagogic paradox: An electron with 4-momentum \( p_\mu \) in the absence of the field takes on quasimomentum \( q_\mu \) once in a field of 4-momentum \( k_\mu \):

\[
q_\mu = p_\mu + \frac{\eta^2m^2}{2k \cdot p} k_\mu, \quad q^2 = \bar{m}^2.
\]

In our experiment \( \eta^2m^2/2k \cdot p \) takes on a fractional value.
Summary of Motivation and Goals

- The Higgs mechanism implies that elementary particles have important interactions with strong background fields.
- Only with electromagnetism can intense, controllable, macroscopic fields be created in the laboratory.
- Explore the validity of QED for electromagnetic field strengths in excess of the ‘critical field strength’
  \[ E_{\text{crit}} = \frac{m^2 c^3}{e\hbar} = 1.6 \times 10^{16} \text{ V/cm}. \]
- Explore QED in the realm where multiphoton interactions dominate, i.e., when \( \eta \equiv \frac{eE}{m\omega_0 c} \approx 1 \).
Proposal for a

STUDY OF QED AT CRITICAL FIELD STRENGTH
IN INTENSE LASER–HIGH ENERGY ELECTRON COLLISIONS
AT THE STANFORD LINEAR ACCELERATOR

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1. Compton Polarimetry

- Both the E-144 laser and electron beams are polarized.
- Compton polarimetry provides a basic check of the E-144 apparatus, as well as a confirmation of the SLC beam polarization.

2. Nonlinear Compton Scattering: \( e + n\omega_0 \rightarrow e' + \omega \)

- Semiclassical theory \( \Rightarrow \) data will diagnose laser intensity.
- Provides high-energy-photon beam for light-by-light scattering.

3. Multiphoton Breit-Wheeler Process: \( \omega + n\omega_0 \rightarrow e^+e^- \)

- Might show anomalous structure in \( e^+e^- \) invariant mass when \( E > E_{\text{crit}} \).
Experimental Ingredients

- Low-emittance electron beam.
- Terawatt laser.
- Synchronization of $e$ and laser beams to 1 psec in time, and a few $\mu$m in space.
- Silicon calorimeters for ‘coarse-grain’ detection of $e^-$, $e^+$ and $\gamma$’s.
- CCD pair spectrometer for ‘fine-grain’ measurements.
- Data-acquisition system based on PC’s interconnected via a local ethernet.
E-144 is at the End of the FFTB
TeraWatt Laser Via Chirped-Pulse Amplification

1 Joule in 1 ps ⇒ $10^{12}$ Watt.

Diffraction limited spot area $\approx \lambda^2 (f/D)^2 \approx 10 \, \mu m^2$.

⇒ $I \approx 10^{19} \, W/cm^2$.

High power pulses can damage optics!

⇒ stretch pulse, then amplify and compress.

E-144 Laser Schematic

Phase stabilized cw Nd:YLF oscillator

476MHz from linac

10nJ, 50ps

1 km optical fiber

1nJ, 200ps

700ps
timing adjust

Pockels cell

Double pass 6mm Nd:glass amplifier

2x spatial filters

1mJ

Nd:glass regenerative amplifier

Anamorphic expansion

10mJ

2x

4x cylindrical

3J

Nd:glass SLAB amplifier

spatial filter

2J, 1.5ps, 1.053μm

KDP crystal

1J, 1.5ps, 0.527μm

0.5Hz

compression stage

To electron beam
synchronization block diagram
Electron & Positron Spectrometers

ECAL, PCAL: silicon-tungsten
ECAL: 3 towers
PCAL: 4 towers
1 tower = 4x4 pads
1 pad = 1.6x1.6 cm²
23 layers of 1 $X_0$
Measurement of $e$-Beam Polarization (May ’94)

Fit to measured polarization asymmetry in 4 energy bins yields

$$P_e P_{\text{laser}} = 0.81 \pm 0.01.$$  

Laser polarization $> 0.96 \Rightarrow P_e = 0.81^{+0.04}_{-0.01}$.  

![Plot of Compton asymmetry vs. ECAL row number with data points for right and left polarizations.](image)
Nonlinear Compton Scattering

(a) \[ e + n\omega_0 \rightarrow e' + \omega \]

(b) Background: multiple Compton scattering

Can distinguish process (a) from (b) by detecting scattered photon.

In first experiments, only the scattered electron was detected.
Theoretical Predictions for $e + n\omega_0 \rightarrow e' + \omega$

Circular polarization (Nikishov et al., JETP 20 (1965) 622).

$$\frac{d\text{Rate}_n}{dE_{e'}} = \frac{4\pi r_0^2 N_{\text{laser}} N_e}{x E_e} \times \left\{ \left(2 + \frac{u^2}{1 + u}\right) \left[J_{n-1}^2(z) + J_{n+1}^2(z) - 2J_n^2(z)\right] - \frac{4}{\eta^2} J_n^2(z) \right\},$$

$$x = \frac{4\omega_0 E_e}{m^2}, \quad u \approx \frac{E_e}{E_{e'}} - 1, \quad z = \frac{2\eta}{x} \sqrt{nu x - u^2(1 + \eta^2)}.$$

Case of linear polarization is more intricate.

$\eta = 0.64$
Effect of Laser and Electron Beam Spots

Beams cross at 17°.

Laser pulse is $\approx 2$ ps long, focussed to $\approx 5\lambda_0$.

Electron pulse is $\approx 5$ ps long.

$$\eta_{\text{max}} = 0.64$$
Measurements of Nonlinear Compton Scattering


18,000 infrared laser shots ($\omega_0 = 1.15$ eV):

16,000 green laser shots ($\omega_0 = 2.3$ eV).
**x-t Scans**

Vary \( x \) and \( t \) offsets between laser and electron beam.

Detect scattered electrons in (a) \( n = 1 \) region and (b) \( n = 2 \) region.

Nonlinear scattering confined to core of laser spot where intensity is the highest.
Observed Rates vs. Laser Intensity

Cross-section not a useful concept for nonlinear scattering.

Plot differential rates normalized to total scattering rate (= total rate of scattered photons).

Normalized to total scattered photon rate
\[ \Rightarrow \text{Rate(order } n) \propto I^{n-1}. \]
Observed Scattering Rates vs. Electron Energy

\[ n = 2 \text{ edge at } 17.6 \text{ GeV}, \, n = 3 \text{ edge at } 13.5 \text{ GeV}. \]

Shaded = full simulation.

Striped = multiple-\((n = 1)\) scattering only.
Measurements of the Scattered Photon

Multiple Compton scatters produce no photons with energy above the maximum for a single scatter.

⇒ No backgrounds for \( n > 1 \) nonlinear Compton Scattering

However, no simple spectrometer for high-energy photons:

We convert the photons to \( e^+e^- \) pairs and analyze the latter in a magnetic spectrometer with CCD detectors.
Making Positrons the Old-Fashioned Way

Bethe-Heitler (1934): A real photon combines with a virtual photon from the field of a nucleus to create an $e^+e^-$ pair.

Nuclear electric fields are strong but not critical; Bethe-Heitler pair creation is well described in perturbation theory involving a single virtual photon.
$e^+$ and $e^-$ from Converted Compton Photons

![Single-arm track spectrum (Run 15296, preliminary)]

- Total: $2578.1 \pm 61$
- Over 30 GeV/c: $68.1 \pm 9$
- Ratio: $0.026 \pm 0.004$
- Expected ratio for $\eta = 0.3$: $0.026$

![N2/N1 vs. EC37](N2/N1 vs. EC37)
Threshold: $\hbar \omega_1 \hbar \omega_2 = (mc^2)^2$

Cross section near threshold: $\sigma_{\text{B-W}} \approx \pi r_e^2 \sqrt{1 - \frac{m^2 c^4}{\hbar \omega_1 \hbar \omega_2}}$. 
Pair Creation by Light

Two step process: \( e + \omega_0 \rightarrow e' + \omega \), then \( \omega + n\omega_0 \rightarrow e^+e^- \).

Multiphoton pair creation is cross-channel process to nonlinear Compton scattering.

\( \Rightarrow \) Similar theories [sums of Bessel functions whose arguments depend on \( \eta^2 \)].

\( \Rightarrow \) Breit-Wheeler cross section in weak-field limit.

\( \omega_{\text{max}} \approx 29 \text{ GeV} \) for 46.6-GeV electrons + \( (n = 1) \) green laser.

Then need at least \( n = 4 \) laser photons to produce a pair.

\( \iff \) Below threshold for 2-photon pair creation.
Trident Production

\[ e + n\omega_0 \rightarrow e' e^+ e^- \]

Laser photon

Background when scattering occurs in presence of electron beam.

Theory only approximate: Weizsäcker-Williams + multiphoton Breit-Wheeler.

Predicted to have rate only 1\% that of the two-step process.
\[ \approx 10^7 \text{ electrons per laser shot from Compton scattering,} \]
\[ \Rightarrow \text{Only detect } e^+ \text{ from } e^+e^- \text{ pair.} \]

Predicted positron spectra:
Laser-Off Positron Backgrounds

Laser-off positrons are from showers caused by electrons that have fallen out of the beam.

1. Bremsstrahlung.

2. Bethe-Heitler pair creation.

Study with data collected with laser off but electron beam on.
1. ‘Signal’ positrons from a wire at IP1 (no laser)

2. Define signal region for laser-on and -off data.
Evidence for Positron Production (August ’96)

178 laser-on candidates - $0.175 \times 398$ laser-off candidates,

$\Rightarrow 106 \pm 14$ signal positrons (upper plots, no $\eta$ cut)

Lower plots: $\eta > 0.216 \Rightarrow 69 \pm 9$ signal positrons.
Positron Rate vs. $\eta$

Rate $\propto \eta^{2n}$ where $n = 5.1 \pm 0.2$ (stat.) $^{+0.5}_{-0.8}$ (syst.):

Normalized to Compton scattering rate:
Strong Field Pair Creation as Barrier Penetration

For a virtual $e^+e^-$ pair to materialize in a field $E$ the electron and positron must separate by distance $d$ sufficient to extract energy $2mc^2$ from the field:

$$eEd = 2mc^2.$$  

The probability of a separation $d$ arising as a quantum fluctuation is related to penetration through a barrier of thickness $d$:

$$P \propto \exp \left(-\frac{2d}{\lambda_C}\right) = \exp \left(-\frac{4m^2c^3}{e\hbar E}\right) = \exp \left(-\frac{4E_{\text{crit}}}{E}\right) = \exp \left(-\frac{4}{\Upsilon}\right).$$

$$R_{e^+} \propto \exp\left[(-2.8 \pm 0.2 \text{ (stat.)} \pm 0.2 \text{ (syst.)})/\Upsilon\right].$$
Comments on Positron Observations

Signal rate $\approx 1$ positron per 10 $e$-laser collisions at highest $\Upsilon$.

The laser-induced positrons are $> 99\%$ from light-by-light scattering and $< 1\%$ from trident production.

In $n\omega_0 + \omega \rightarrow e^+e^-$ the average number $n$ of laser photons is 5 (plus 1 more to produce the high-energy photon by Compton backscattering).

This is the first observation of positron production in light-by-light scattering with only real photons.
Reports in the Popular Media

http://www.slac.stanford.edu/exp/e144/popular.html/


*Materie aus Licht*, Neue Zurich Zeitung, Sept. 26, 1997;
*Materie aus Licht erschaffen*, Oct. 1, 1997,


*Let There Be Matter*, a 2:04 min. interview by Karen Fox for the AIP Science Report

To Do: Basic Physics

1. Study the mass-shift effect in nonlinear Compton scattering.
   - Continue at SLAC, or use 50-Mev electrons and CO\textsubscript{2} laser at BNL.

2. Study pair creation in a pure light-by-light scattering situation:
   - No trident production.
   - Search for structure in the $e^+e^-$ invariant-mass spectrum.
   - Upgrade laser to 10-Hz, 100-femtosecond pulses with $\Upsilon_{\text{max}} \approx 5$. 
To Do: Applied Physics

1. Copious $e^+e^-$ Production.
   - $e^+e^-$ pairs from $e$-laser collisions could be best low-emittance source of positrons.
   - No Coulomb scattering in laser ‘target.’
   - Positrons largely preserve the geometric emittance of the electron beam ⇒ ‘cooling’ of invariant emittance.
   - Can produce 1 positron per electron if $E^* > E_{\text{crit}}$.
   - Production with visible laser is optimal for $\sim 500$ GeV electrons.
     [Or use a 50-nm FEL with 50-GeV electrons.]

2. High-energy $e$-$\gamma$ and $\gamma$-$\gamma$ colliders.
   - $e$-laser scattering can convert essentially all of an electron beam to a photon beam.

3. Picosecond/femtosecond pulsed-$\gamma$ sources from Compton backscattering.
Vacuum Laser Acceleration?

• A Maxwellian view: acceleration (energy gain) of a charge is due to interference between the drive field and the “spontaneous radiation” of the charge.

• Ex: The energy gained by a electron as it moves across the gap of a capacitor is compensated by a loss of field energy due to the interference between the DC field and the dipole field of charge + image.

• Ex: The energy gained by an electron in an rf cavity is compensated by the energy of interference between the cavity field and transition radiation of the charge.

• In these examples, the energy gain is linear in the strength of the external field.

• ⇒ No vacuum linear acceleration (i.e., linear in the laser field strength).

• Weak quadratic acceleration is possible in vacuum.

• http://puhep1.princeton.edu/~mcdonald/accel/