Kirk conjures Matter from Light

Pair creation in photon-photon inelastic scattering

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D.L. Burke et al., PRL 79. 1626 (1997)
PROPOSAL FOR EXPERIMENTAL STUDIES OF NONLINEAR QUANTUM ELECTRODYNAMICS

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The Physics of photon-photon scattering

\[ 4 \omega_1 \omega_2 > (2mc)^2 \]

\[ \sigma \sim \left[ \frac{\omega_1 \omega_2}{m^2 c^4} \right]^3 \mu b \]

\[ \sigma (\mu b) \]

\[ \sqrt{\frac{\omega_1 \omega_2}{mc^2}} \]}
Need High Energy Photons: obtain by backscattering the laser photons from highly relativistic electrons

\[ \omega = \text{incident photon frequency} \quad \hbar \omega = 2.34 \text{ eV} \]
\[ \omega' = \text{scattered photon frequency} \quad \hbar \omega' = 27 \text{ GeV} \]
\[ \gamma = \frac{E_e}{mc^2} \quad \text{normalized electron energy} \quad 9 \times 10^4 \]

\[ \omega_{\text{max}}' = 4 \gamma^2 \omega / [ 1 + 4 \gamma \hbar \omega / mc^2 ] \approx 27 \text{ GeV} \]

In these conditions the recoil term, \[ 2 \gamma \hbar \omega / mc^2 \approx 1 \]
therefore we speak of Compton scattering
Experiment to demonstrate the nonlinear properties of the vacuum

In real space

Laser focus
\( \lambda = 527 \text{ nm} \)

Feynman graphs
LAYOUT OF THE EXPERIMENT
THE LASER SYSTEM

476 MHz from linac

Phase-stabilized Nd:YLF oscillator

119-MHz pulse train

800-m fiber

Expansion gratings

Pockels cell

Double-pass 6-mm Nd:glass

10 mJ

2×

Nd:glass regenerative amplifier

Anamorphic expansion

2×

Nd:glass SLAB amplifier

3 J

4× cylindrical

1×

KDP crystal

To experiments

1.25×

2×

10 mJ

2×

2×
**LASER PULSE PARAMETERS**

\[ \lambda = 527 \text{ nm} \rightarrow \hbar \omega = 2.34 \text{ eV} \]

\[ U = 1 \text{ J} \quad \tau_{\text{FWHM}} = 1.7 \times 10^{-12} \text{ s} \quad \text{Area} = 30 \mu\text{m}^2 \]

Derived properties

Terawatt laser

- Power = \( 0.6 \times 10^{12} \) W
- Intensity = \( 2 \times 10^{18} \) W/cm\(^2\)
- \( E = 3.9 \times 10^{10} \) V/cm
- \( \rho = 1.8 \times 10^{26} \) photons/cm\(^3\)

**ELECTRON BEAM PARAMETERS**

\[ E_e = 46.6 \text{ GeV} \]

\[ N = 5 \times 10^9 \text{ electrons/pulse} \]

\[ \sigma_x = \sigma_y = 60 \mu\text{m} \quad \sigma_z = 0.5 \text{ mm} \rightarrow \tau_{\text{FWHM}} = 4 \text{ ps} \]
Final Focus Test Beam in the SLAC Switchyard
LAST STAGE OF THE LASER SYSTEM
Slab amplifier and compression gratings
THE ELECTRON BEAM LINE and the LASER–e− INTERACTION CHAMBER
Overlap in time (synchronization) of LASER and ELECTRON pulses

- Use a subharmonic of the accelerator frequency (2856 MHz) to drive the laser modelocker (119 MHz).
Overlap in space of LASER FOCUS and ELECTRON pulses

The electron beam must cross through the focus of the laser beam.
Non linear (multiphoton) Compton Scattering

$n$ is the number of photons absorbed

The plots are for incident IR laser $\lambda = 1054$ nm

Photon energy in GeV, for IR laser

Electron energy in GeV, for IR laser
Forward going $\gamma$-rays measured in CCD pair spectrometer extend **beyond** the single photon Compton limit.
Recoil electrons measured in the $e$-calorimeter extend **below** the single photon Compton limit of 17.6 GeV for green laser

n=2 plateau

Dashed curves are for “plural scattering”

n=3 plateau
Scattered electron yield as a function of laser intensity

\[
\frac{1}{N} \frac{dN}{dp} \propto (\text{Intensity})^{n-1}
\]
Serendipity

In the proposal we planned to use two interaction regions: the first to produce the high energy $\gamma$, and the second for the $\gamma$ to collide with the laser beam... Of course, the $\gamma$ collides within the same laser pulse in which it is produced... and it suffices to detect the positron to establish the production of a pair!!

The original scheme was technically too challenging to have worked!!

The beam trace after the FFT final focus. The vertical dimensions are amplified by a factor of 100.

Note the location of the two proposed interaction regions, IP1 and IP2.
IDENTIFICATION OF POSITRONS

Measure energy in calorimeter cluster \( E_{\text{cluster}} \)
Measure momentum from impact position \( p_{\text{cluster}} \)
For positrons (no multiple hits) \( E_{\text{cluster}}/p_{\text{cluster}} = 1 \)

Test data obtained by inserting a thin wire instead of the laser at the focus
Spectrum of observed positrons

Momentum spectrum symmetric around $p = E_\gamma / 2 = 13 \text{ GeV}$
POSITRON YIELD vs. LASER FIELD STRENGTH

Process involving $n$ laser photons has probability

$$P \sim \eta^{2n} \quad \text{where} \quad \eta^2 = \left(\frac{eE}{\omega mc}\right)^2 = \left(\frac{e}{\omega mc}\right)^2 z_0 I$$

Number of positrons per laser shot

Fit $n = 5.1 \pm 0.2$

Background limit

$\eta$ at laser focus

$10^{-1}$

$10^{-2}$

$10^{-3}$
OBSERVED and CALCULATED RATE OF POSITRON PRODUCTION

- Exact calculation

\[ e^- + \omega_0 \rightarrow e^- + \gamma \]

- Agrees with data

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

Note log-log scale
Breakdown of the Vacuum

J. Schwinger  Phys. Rev. 82, 664 (1951)

Define critical field  \( E_c = \frac{mc^3}{e\hbar} \)  and  \( Y = \frac{E}{E_c} \)

The probability for pair production is

\[
W = \alpha \left( \frac{E}{\pi} \right)^2 e^{-\pi/Y}
\]

In our case the Lorentz boosted E-field seen by the high energy photon leads to

\[
Y_Y = \left( \frac{2\mathcal{E}_Y}{mc^2} \right) (E_{\text{rms}}/E_c)
\]
POSITRON YIELD vs. 1/Y

Fit to \( e^{-\alpha/Y} \rightarrow \alpha = 2.02 \pm 0.12 \)

but \( \alpha' = \alpha \sqrt{2} \left( \frac{30}{46.6} \right) = 1.84 \pm 0.11 \)

predicted \( \alpha' = \pi g(\eta) = 2.06 \)
The cast of characters

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Supplementary Slides
FREQUENTLY MISSED POINT

A single laser beam can not produce $e^+e^-$ pairs

TO PRODUCE A MASSIVE PAIR THE INVARIANT

$I = E^2 - B^2$ must be $> 0$

STATIC ELECTRIC FIELD $I > 0$
STATIC MAGNETIC FIELD $I < 0$
E.M. FIELD $I = 0$

A standing wave is OK, but this is equivalent to photon-photon scattering.

EXAMPLE: Using colliding x-ray beams from Free Electron Lasers

$\lambda = 0.1$ nm $\rightarrow \hbar \omega = 12$ keV  If $\sigma = 0.1$ nm, $\Delta t =0.1$ fs

and $P = 4.5$ TW  30 $e^+e^-$ pairs are produced per pulse
LASER PULSE – ELECTRON BEAM SYNCHRONIZATION

Laser - electron synchronization
Goal: 1 ps

Diagram showing the synchronization process involving demodulation, optical modulation, laser beam, and photodiode connections.
STRONG FIELD QED \( E \geq E_c \)

FIELD IN THE FOCUS OF AN INTENSE LASER BEAM

\[
I_L = 10^{18} \text{ W/cm}^2 \quad \rightarrow \quad E_L = \sqrt{2Z_oI_L} = 2.75 \times 10^{10} \text{ V/cm}
\]

But if a 50 GeV electron \( (\gamma = E_e/mc^2 = 10^5) \) traverses the focus,

IN THE ELECTRON REST FRAME

\[
E^* = 2\gamma E_L = 5.5 \times 10^{15} \text{ V/cm} \approx 0.4 \ E_c
\]

STRONG FIELDS ARE ALSO FOUND IN:

- “ATOMS” WITH \( Z \geq 137 \)
- HEAVY ION COLLISIONS
- CHANNELING OF RELATIVISTIC ELECTRONS
- ASTROPHYSICAL ENVIRONMENTS (MAGNETIC FIELDS)
1929  Klein Paradox
1936  Heisenberg-Euler Lagrangian
1951  Schwinger Critical Field

A virtual $e^+e^-$ pair travels a distance

$$\lambda_c = \frac{\hbar}{mc}$$

If the energy gained in that distance in a static electric field, equals the electron rest mass

$$eE\lambda_c = mc^2$$

The field will spontaneously break down into $e^+e^-$ pairs

$$E_c = \frac{m^2c^3}{e\hbar} = 1.32 \times 10^{16} \text{ V/cm}$$
EM PROCESSES IN STRONG FIELD QED
(Multiphoton Processes)

PERTURBATIVE

Dimensionless Invariant Coupling (Instead of $e/\sqrt{\hbar c}$)

$$\eta = e \left( \sqrt{\langle A^\mu A_\mu \rangle} \right)/mc = eE/\omega mc$$

A classical parameter (no $\hbar$). It diverges as $\omega \rightarrow 0$. When $\eta \geq 1$ relativistic effects are important. Processes involving $n$ photons are proportional to $\eta^{2n}$

NON-PERTURBATIVE

$$Y = E^*/E_c = 2\gamma eE_L \hbar/(m^2c^3)$$

When $Y \geq 1$ pair production is dominant.

Probability/V-T = $(\alpha E^2/\pi^2\hbar)\exp(-\pi/Y)$