The Schwinger plasma: An experimental program to study the plasmas that exist inside the vacuum

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The Bucksbaum Group studies motion on the quantum-scale induced and controlled by strong fields

- **Attosecond electron motion across molecules induced by x rays or strong fields**
  - James Cryan, Ruaridh Forbes, Andrei Kamalov, Jordan O’Neal, Nick Werby, Anna Wang: **Supported by DOE-BES-CSGB**

- **Strong-field femtosecond laser-molecule quantum control**
  - Ruaridh Forbes, Andy Howard, Greg McCracken, Chelsea Liekhus-Schmaltz; **Supported by NSF**

- **Ultrafast X-ray diffraction for molecular movies**
  - Adi Natan, Matt Ware, Mike Glownia, James Cryan, Ian Gabalski; **Supported by DOE-BES-CSGB**

- **Strong-fields beyond the Schwinger limit**
  - Sebastian Meuren, David Reis; **Supported by DOE-FES**

Come to the Ford Distinguished Lecture in UM Physics on February 12, 2020 to hear about this.
What is the vacuum? Not exactly nothing…

- Occupies all space
- Has no charge
- Has no angular momentum (isotropic)
- Has no preferred origin (homogeneous)
- Non-dispersive (c(λ)=constant)
- Maxwell's Equations for fields in the vacuum:
  \[ \nabla \cdot \vec{E} = 0 \quad \nabla \times \vec{E} = -\frac{1}{c} \frac{\partial \vec{B}}{\partial t} \]
  Both Lorentz and gauge invariant

  \[ \nabla \times \vec{B} = \frac{1}{c} \frac{\partial \vec{E}}{\partial t} \quad \nabla \cdot \vec{B} = 0 \]

- Energy density = ?Zero?? Maybe not…
All particles and fields in quantum mechanics have "Zero Point Energy"

Example: Harmonic Oscillator

\[ H = \frac{p^2}{2m} + \frac{1}{2} m \omega^2 q^2 \]

\[ \dot{q} = [q, H] = i \hbar \frac{p}{m} \]

\[ \dot{p} = [p, H] = -i \hbar m \omega q \]

\[ H = \hbar \omega (N + \frac{1}{2}) \]

ZPE

Light has it, too

\[ H = \hbar \omega (N_k + \frac{1}{2}) \]

Each mode has \( \text{ZPE} = \frac{1}{2} \hbar \omega \)

Number of modes:\n\[ \frac{V}{8\pi^3} \sum \int d^3 k \]

ZPE density is:\n\[ \frac{2}{8\pi^3} \int d^3 k \left( \frac{1}{2} \hbar \omega \right) \]

Over a finite frequency range:\n\[ p_0(\omega_1, \omega_2) = \frac{\hbar}{8\pi^2 c^2} (\omega_2^4 - \omega_1^4) \]

How much? I did the math: 50 visible-wavelength photons / \( \mu^3 \);

Or about 100 kW of visible ZPE entering and leaving your eyes -- in the dark.
If the vacuum contains radiation, then it also contains matter from pair-production by vacuum modes with $\hbar \omega \geq 2mc^2$:

Heisenberg Uncertainty relation sets the scale:
$\Delta E \Delta t \geq \hbar$, with $\Delta E = 2mc^2$

Virtual pair "lifetime" $\Delta t = \hbar / 2mc^2$
$= 0.6$ billionths of a femtosecond (0.6 yoctoseconds)

Virtual pair "size" $= 2\hbar / mc = 2\lambda_c$
$= 0.39$ femtometers

Dirac's View: Vacuum is like an insulator with a negative energy "sea" filled with electrons.

Quantum fluctuations create virtual electron-"hole" pairs --

A PLASMA IN THE QUANTUM VACUUM
Interrogating the quantum vacuum plasma with an external field $F$

Fowler-Nordheim tunneling

\[ \sim e^{-\frac{4}{3} \frac{4m^2c^3}{e\hbar F}} = e^{-\frac{16}{3} \frac{F_{cr}}{F_L}} \]

\[ F_{cr} = \frac{mc^2}{e\lambda_c} \]
Interrogating the quantum vacuum plasma with an external field $F$

Incorporate relativity (Dirac Equation)

\[
\frac{j_{\text{trans}}}{j_{\text{incident}}} = \frac{e^{-\pi F_{\text{cr}}/F_L}}{1 - e^{-\pi F_{\text{cr}}/F_L}}
\]

This is a Fermi-Dirac distribution where each mode tunnels with probability

\[
P_n = e^{-\pi F_{\text{cr}}/F_L}
\]


\[
\frac{F_L}{F_{\text{cr}}} = \frac{eF_L\lambda_C}{mc^2} = \frac{\text{work done over} \lambda_C}{mc^2}
\]

\[
F_{\text{cr}} = \frac{m^2c^3}{\epsilon h} = 1.3 \times 10^{16} \, V/cm, \text{ the Schwinger critical field}
\]

\[
I_{\text{cr}} = \frac{F_{\text{cr}}^2}{4\pi} = 2.2 \times 10^{29} \, W/cm^2. \quad \text{So how big is that?}
\]
Big enough to pull electrons out of the vacuum during quantum fluctuations:

Virtual pair "lifetime" = $\hbar/2mc^2$
Virtual pair "size" = $2\hbar/mc = 2\lambda_c$
Work done on a virtual pair over its lifetime
$$|e|F_{cr}2\lambda_c = 2mc^2$$
Or, in relativistic units:
$$F_{cr} = \frac{m^2c^3}{e\hbar} = 1.3 \times 10^{16} \text{ V/cm}$$
$$I_{cr} = \frac{F_{cr}^2}{4\pi} = 2.2 \times 10^{29} \text{ W/cm}^2$$

A uniform (or low frequency laser) field of $F_{cr}$ does work $2mc^2$ on a virtual $e^+e^-$ pair in a distance on the order of the Compton wavelength $\lambda_c = \hbar/mc$, implying the instability of the vacuum under $e^+ - e^-$ pair creation.

What laser properties really matter for this application? Laser field amplitude $F_L$

Lorentz-invariant dimensionless quantities related to $F_L$:

$$\eta = \frac{e F_L \lambda_L}{2\pi mc^2} = \frac{\text{work done in 1 radian of laser wavelength}}{mc^2}$$

$$a_0 = \frac{e F_L}{\omega_L mc} = \frac{\text{momentum transferred in 1 radian of laser period}}{mc}$$

Dimensionless figure of merit for breaking the vacuum:

$$\Upsilon = \frac{e F_L^* \lambda_C}{mc^2} = \frac{\text{work done over } \lambda_C}{mc^2} = \frac{F_L^*}{F_{cr}}$$

($F_L^*$ is in the CM frame for the pair)

When $\Upsilon = 1$, the quantum vacuum breaks down into $e^+e^-$ pairs.
Paradigm shift from QED to SFQED

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

\[ \gamma + n\hbar\omega \rightarrow e^+ + e^- \]

\[ \gamma + \vec{A}_L(\vec{x},t) \rightarrow e^+ + e^- + \vec{A}_L(\vec{x},t) \]
Non-linear/non-perturbative QED

\[ \eta = \frac{e}{mc^2} \sqrt{\langle A_\mu A^\mu \rangle} = \frac{eE\lambda}{2\pi mc^2} \]

\[ \gamma = \frac{e\hbar}{m^3 c^5} \sqrt{\langle (F_{\mu\nu}p^\nu)^2 \rangle} = \frac{eE^*\lambda}{2\pi mc^2} = \frac{\lambda}{\lambda^*} \]

Dressed state (Furry, Volkov, …)

Photon emission

Multi-photon Compton
Quantum radiation reaction

...
Magnetars are spinning neutron stars that contain B fields above the Schwinger critical value.

Map of magnetars detected in our galaxy

Surface magnetic fields (inferred from $P$ and $\dot{P}$)

Dense e+e- plasmas produced by Breit-Wheeler pair production at a surface create a dense beam of gamma rays.

Above the Schwinger threshold colliding laser beams decay into a cloud of e+e- plasma, a "QED Cascade."

Breaking the vacuum in the lab: First breakthrough: CPA, circa 1985, started with the "Table-top Terawatt" laser

First breakthrough: CPA, circa 1985, started with the "Table-top Terawatt" laser

Two happy people in Stockholm last year:

D. Strickland and G. Mourou,
That T³ laser (in Rochester, not Michigan) was used to pull electrons out of atoms. It was a start...

\[ E_c = \alpha^4 mc^2 / r_e = 2I_p / a_0 = 5 \times 10^9 \text{V/cm} \]

Where is high intensity physics going?

\[ -I_p \]

Schwinger limit

\[ 10^{25} \text{ W/cm}^2, \text{ Fully stripped U} \]

\[ 10^{20} \text{ W/cm}^2, \text{ Fully stripped Ar} \]

atomic

\[ E_c = \frac{\alpha^4 mc^2}{r_e} = 2I_p/a_0 = 5 \times 10^9 \text{V/cm} \]

vacuum

\[ E_c = \frac{\alpha mc^2}{r_e} = I_p/\lambda_c = 1.3 \times 10^{16} \text{V/cm} \]
Later refinements have brought us to the petawatt frontier illustrated by the Mourou plot.

The pulse is now long and low power, safe for amplification.

A pair of gratings disperses the spectrum and stretches the pulse by a factor of a thousand.

High energy pulse after amplification.

A second pair of gratings reverses the dispersion of the first pair, and recompresses the pulse.

Focused Intensity (W/cm²)

\[ Y = 1 \text{ (Schwinger intensity)} \]

\[ U_P = m_e c^2 \]

\[ U_P = 1 \text{ atomic unit} \]


Michigan \rightarrow LLNL \rightarrow Texas Rutherford \rightarrow CPA \rightarrow Q-switching

\[ \text{OPCPA} \]

Nd:Glass

Ti:sapphire

OPCPA
Most of these lasers are being built for high field discovery science

The comprehensive Mourou plot:

PW-class lasers: concentrated in Europe

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Attosecond Light Pulse Source (Szeged, Hungary)
-Ultrafast light sources, and coherent x-ray sources
-PW drive laser
-Several beam lines, from 10KHz 100 mJ to 0.1 Hz 300J

High Energy Beam-Line Facility (Prague, Czech Republic)
Beam lines from -200mJ to 1.3kJ lasers, including 2 10PW lasers;
Six experimental areas, including exotic physics, acceleration, x-rays, materials science.

Nuclear Physics Facility (Magurele, Romania)
2 multi-petawatt, 200J, 0.1Hz, <30fs lasers
Compton backscatter gamma ray source
Experiments aimed at nuclear physics.

$10^{23} - 10^{24}$ W/cm$^2$
@Beamlines and NP
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China plans to dominate this technology, and probably will, with plans for a 100 PW system based on Optical Parametric CPA:

- **Main specifications:**
  - Focused intensity $1 \times 10^{23} \text{ W/cm}^2$;
  - Peak power 100 PW;
  - Pulse duration 15fs;
  - Focused spot 5$\mu$m diameter;
What's one Petawatt after all? Not enough for our needs.

- 100 J in 100 fs, at $\lambda=800$ nm, focused to 10µm $\Rightarrow 10^{21} \text{W/cm}^2$.
- The total energy, 100 Joules, is about the kinetic energy of a pitched baseball, calories in a potato, 10x the energy in a SLAC electron bunch.
- The peak power, 1 PW, is nearly 100x the world's power consumption rate.
- The focused intensity is greater than the center of the sun. The rms electric field is 100 trillion V/m.
- $F_L = 10^{12} \text{V/cm}$, only $10^{-4}F_{cr}$

What is a petawatt laser pulse?
SFQED is featured prominently in the recent NAS "Reaching for the Brightest Light" PW laser report.

5.7 EXTREME INTENSITY: TOWARD AND BEYOND THE SCHWINGER LIMIT OF $10^{14}$ PW/cm$^2$

5.7.1 Introduction ...................................................................................................................
5.7.2 The Schwinger Limit ......................................................................................................
5.7.3 Vacuum Polarization: Matter from Light .................................................................
5.7.4 Nonlinear Thomson and Compton Scattering .........................................................
5.7.5 Radiation Reaction ....................................................................................................... 
5.7.6 Vacuum Polarization: Elastic Light Scattering ........................................................
5.7.7 Beyond the Standard Model ............................................................................................

Full report http://nap.edu/24939
1) The science is important.
2) Applications exist in several areas.
3) The community is large but fragmented.
4) No cross-agency stewardship exists.
5) The US has lost its previous dominance.
6) Co-location of intense lasers with existing infrastructure is essential; key US advantage over ELI
7) University/Laboratory/Industry cooperation is necessary to retain and renew the talent base.
Here's what makes collocation essential:

- Intensity of the laser in the CM frame of a relativistic electron scales as $4\gamma^2$.
- Fundamental physics in a new nonperturbative regime
  - Transition from multiphoton to tunneling.
The highest intensity experiment to date is SLAC E144, which pushed lasers off the Mourou plot trend line:

- Near head-on collisions of TW laser (\(\hbar \omega = 2.34 \text{ eV}\)) with backscattered photons, \(\hbar \omega \sim 28 \text{ GeV}\), from 46.6 GeV SLAC beam.
- Need \(\geq 4\) photons to produce a pair (1.02 MeV in COM)
- Intensity in COM frame approaching Schwinger limit (\(\sim 10^{29} \text{ W/cm}^2\)) and QED critical field.
The laser: \( T^3: \text{table-top-TW,} \)
Chirped Pulse Amplification Nd: glass laser

- Mode-locked Nd:YLF synchronized
- to rf cavities to few ps
- Fiber and grating stretcher
- Multi-stage amplification
- Zig-zag SLAB amplifier
- \(~1\text{J, 1.5ps, 0.5 Hz}\)
- 1054 nm fundamental
- 527 nm (KDP)
- \( f/# \) 6 focusing 2X diffraction limit
- \(~10^{18} \text{ W/cm}^2\)
E144 Measured in transition regime

Process involving $n$ laser photons has probability

$P \sim \eta^{2n}$  
where  
$\eta^2 = \left[ \frac{eE}{\omega mc} \right]^2 = \left[ \frac{e}{\omega mc} \right]^2 Z_0 I$

Multi-photon picture

Tunneling Picture (Schwinger)

Fit $n = 5.1 \pm 0.2$

Background limit

Number of positrons per laser shot

$0 \to 0.3$  
$10^{-3} \to 10^{-1}$

Number of positrons per laser shot

$2 \to 10$  
$10^{-4} \to 10^{-2}$

$1/E/E_c$  
$1/Y$

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

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Reaching strong-field regime @FACET-II

Baseline: 20 TW, 13 GeV

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Focused Intensity Frontier

Y = 1 \textit{(Schwinger intensity)}

\begin{align*}
Y > 1 & \text{ possible now} \\
\text{with current facilities (SLAC/DESY...)} \\
\text{and modest laser}
\end{align*}
## FACET-II E-320 collaboration

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**Collaborating Institutions:** Carleton University (Canada), Aarhus University (Denmark), Ecole Polytechnique (France) Max-Planck-Institut für Kernphysik (Germany), Helmholtz-Institut Jena (Germany), Friedrich-Schiller-Universität Jena (Germany), Universidade de Lisboa (Portugal), Queen's University Belfast (UK), California Polytechnic State University (CA USA), Lawrence Livermore National Laboratory (CA USA), Princeton University (NJ USA), SLAC National Accelerator Laboratory (CA USA), University of California Los Angeles (CA USA), University of Colorado Boulder (CO USA), University of Nebraska - Lincoln (NE USA)
E-320 can test various aspects of SFQED

**Tunneling pair production/vacuum breakdown**
- Pair production inside quasi-static field
- Nonperturbative tunneling exponent
- Much higher statistics: >$10^3$ positrons/shot

**Strong-field synchrotron radiation**
- Reduced radiation probability, spectrum: redshift
- Coherent interaction with $\sim 10^2$ laser photons
- Emission of high harmonics (up to 8Gev photons)

Simulations: Tamburini, Vranic, E-320 collaboration
E-320 can test various aspects of SFQED

Breakdown of the Local Constant Field Approximation (LCFA)
- Applicability of the LCFA: vital for numerical codes
- Formation region depends on photon frequency
- LCFA failed: suppression of low-frequency radiation

Quantum radiation reaction (QRR) - energy
- Stochasticity: broadening of the energy distribution
- Quenching: some electrons don't radiate at all
- Quantum corrections to Landau-Lifshitz

Simulations: Tamburini, Vranic, E-320 collaboration
"New" physics: re-collisions.

\[ \eta \gg 1, \gamma \sim 1, \]

Stationary phase approximation,
Tunneling, classical trajectories, re-collisions similar to SF-AMO

Possibility for \( \mu^+ + \mu^-, \pi^+ + \pi^-; \pi^0 \ldots \) productions well below threshold

S. Meuren, 2015

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Summary: Plasmas inside the vacuum

- The vacuum is filled with quantum fluctuations of radiation and particles
- The quantum vacuum is a fundamental plasma frontier
- The entry point for study is fields that exceed the Schwinger threshold of $mc^2/e\lambda_c$
- Experimental studies are enabled by locating petawatt-class lasers together with relativistic particle accelerators

Above the Schwinger threshold, CPA lasers can generate copious quantities of electron-positron pairs emulating conditions in the most energetic parts of the universe.
Thanks!

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