Fundamental Physics with XFELs

Ralf Schützhold

Helmholtz-Zentrum Dresden-Rossendorf
Institut für Theoretische Physik, Technische Universität Dresden

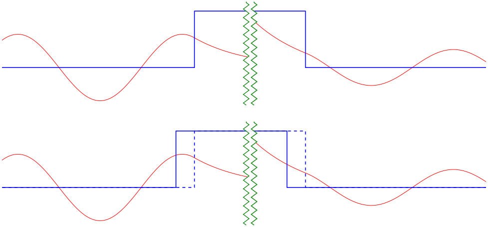
UK XFEL townhall meeting on Fundamental Physics, Quantum Computing and AI, University of Plymouth, 19th January 2024

Dynamically Assisted Quantum Tunneling

S. Coleman: *"Every child knows..."*

$$P \sim \exp\left\{-\frac{2}{\hbar}\int dx\,\sqrt{2m[V(x)-E]}\right\}$$

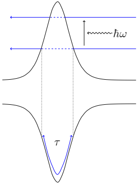
Question: $V(x) \to V(t,x)$?



Here: $V(x)$ plus field $\mathfrak{E}(t)$

- pre-acceleration
- potential deformation
- energy mixing
  $E \to E + \hbar\omega$
- displacement effect
  Kramers-Henneberger frame

C. Kohlfürst, F. Queisser, R.S., Phys. Rev. Research **3**, 033153 (2021)

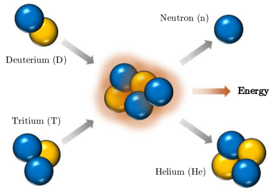


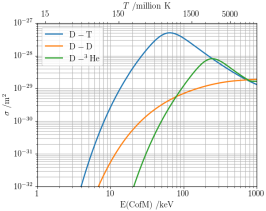
Adiabatic versus non-adiabatic:

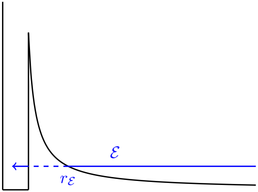
Büttiker-Landauer "traversal" time

$$\mathfrak{T} = \sqrt{m}\int dx\,/\sqrt{2[V(x)-E]}$$

Dynamically Assisted Nuclear Fusion







$$ {}^2_1\mathrm{D} + {}^3_1\mathrm{T} \rightarrow {}^4_2\mathrm{He} + {}^1_0\mathrm{n} + 17.6\ \mathrm{MeV} $$

F. Queisser and R.S., Phys. Rev. C **100**, 041601(R) (2019)

XFEL pulse

$A_x(t) = A_0/\cosh^2(\omega t)$

$\omega = 1$ keV & 10^{16} V/m

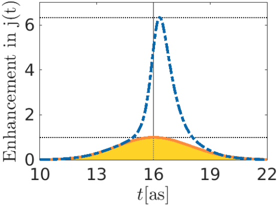
Initial kinetic energy

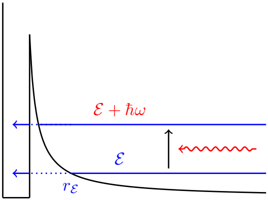
$E = 2$ keV

Oscillating XFEL fields

$\rightarrow$ resonances at $\omega = E$

D.Ryndyk, C.Kohlfürst, F.Queisser, R.S., arXiv:2309.12205





Sauter-Schwinger Effect

F. Sauter, Z. Phys. **69**, 742 (1931); J. S. Schwinger, Phys. Rev. **82**, 664 (1951);...

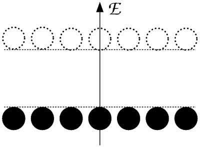
Schrödinger equation (non-relativistic)

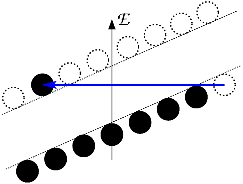
$$i\hbar\frac{\partial}{\partial t}\psi = -\frac{\hbar^2}{2m}\nabla^2\psi + V\psi \rightsquigarrow E = \frac{p^2}{2m} + V$$

Dirac equation (relativistic)

$$\gamma^\mu\left(i\hbar\partial_\mu + qA_\mu\right)\Psi = mc\Psi \rightsquigarrow E = V \pm \sqrt{c^2p^2 + m^2c^4}$$

Positive and negative energy levels → Dirac sea → holes = positrons





Electric field: tilt $V(x) = q\mathfrak{E}x$
→ tunneling from Dirac sea

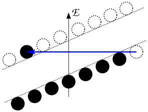
$$\mathfrak{E}_{\text{crit}} = mc^3/(q\hbar) \approx 1.3 \times 10^{18}\text{V/m}$$

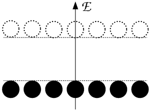
Matter from Light

C.Kohlfürst, N.Ahmadiniaz, J.Oertel, R.S., Phys. Rev. Lett. **129**, 241801 (2022)

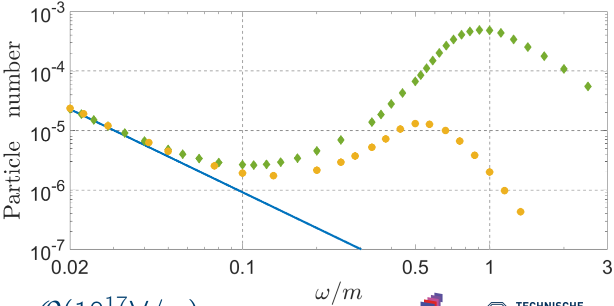
Sauter-Schwinger (non-perturbative) Breit-Wheeler (perturbative)

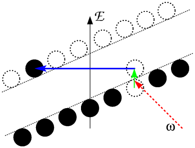





Colliding XFEL pulses (Maxwell equations ✓ transversal fields ✓)





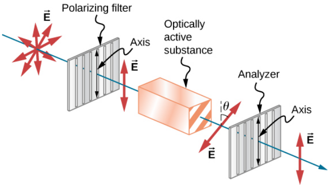
instanton ✓

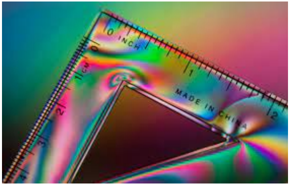
pre-factor ?

WKB ✓

$\mathfrak{E} = \mathcal{O}(10^{17}\text{V/m})\ldots$

Quantum Vacuum Birefringence





- ruler (optically active medium) $\to$ quantum vacuum
- tension $\to$ electromagnetic fields

Light-by-light scattering: Euler-Heisenberg Lagrangian

$$\mathcal{L} = \frac{1}{2}\left(\mathfrak{E}^2 - \mathfrak{B}^2\right) + \frac{2\alpha_{\rm QED}^2}{45 m^4}\left[\left(\mathfrak{E}^2 - \mathfrak{B}^2\right)^2 + 7\left(\mathfrak{E}\cdot\mathfrak{B}\right)^2\right]$$

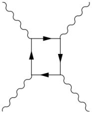
Sub-critical fields

$\mathfrak{E} \ll \mathfrak{E}_{\rm crit} \approx 1.3 \times 10^{18}$ V/m

$\mathfrak{B} \ll \mathfrak{B}_{\rm crit} \approx 4.4 \times 10^{9}$ T

Slowly varying fields

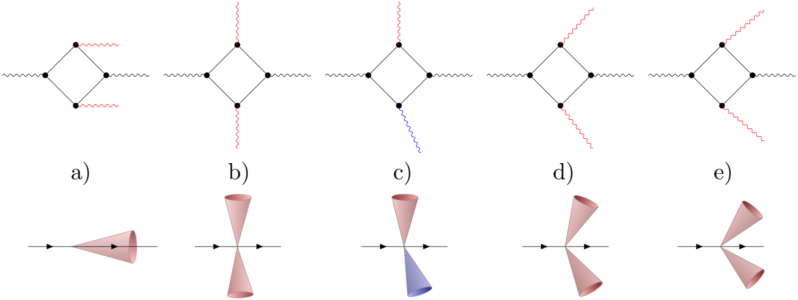
$\hbar\omega, \hbar c k \ll mc^2 \approx 511$ keV



XFEL plus Optical Laser (plus Nuclei?)

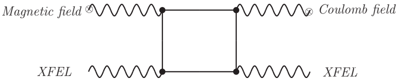
N.Ahmadiniaz, T.E.Cowan, J.Grenzer, S.Franchino-Viñas, A.Laso Garcia, M.Šmíd, T.Toncian, M.A.Trejo, R.S., Phys. Rev. D **108**, 076005 (2023)

XFEL: 10^{12} photons with 6 keV optical: 10^{22} W/cm^2 with 1.5 eV

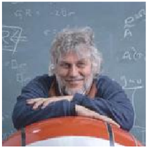


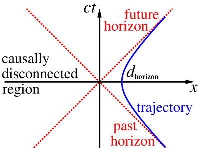
$\mathcal{O}(10^{-3})$ photons $\vartheta = \mathcal{O}(\text{mrad})$ outlook: axions S.Evans, R.S., `arxiv:2307.08345`

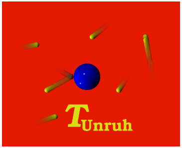
N. Ahmadiniaz, M. Bussmann, T.E. Cowan, A. Debus, T. Kluge, R.S., Phys. Rev. D Lett. **104**, 011902 (2021)

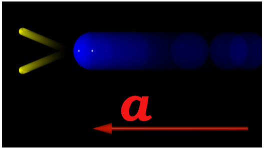


Signatures of the Unruh Effect with XFELs







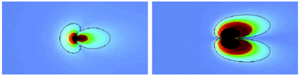


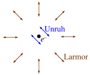
Unruh $P_{\text{Unruh}} \sim (\alpha_{\text{QED}}\mathfrak{E}/\mathfrak{E}_{\text{crit}})^2$ versus Larmor (classical) $1 : 10^7$

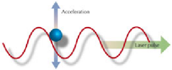
+ blind spot — P. Chen and T. Tajima, Phys. Rev. Lett. **83**, 256 (1999).

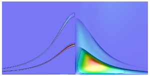
+ entangled pairs — R. S., G. Schaller, and D. Habs, Phys. Rev. Lett. **97**, 121302 (2006).

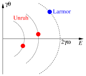
+ polarization + spectrum — R. S., G. Schaller, and D. Habs, Phys. Rev. Lett. **100**, 091301 (2008).



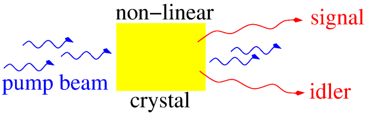








Analogy: parametric down-conversion in quantum optics



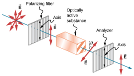
→ Bell states in the keV regime?

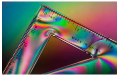
→ interference of many electrons?

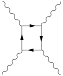
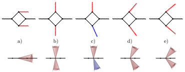
SFB 1242 | TECHNISCHE UNIVERSITÄT DRESDEN | DRESDEN concept | HZDR

Summary

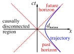
$\mathfrak{E} \geq \mathcal{O}(10^{12}\text{V/m})$ vacuum birefringence optical: 10^{22} W/cm^2

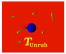


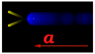


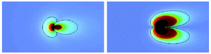
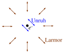




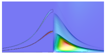
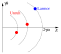
$\mathfrak{E} \geq \mathcal{O}(10^{12}\text{V/m})$ signatures of the Unruh effect 10^9 coherent e^-

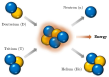


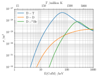
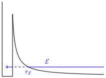
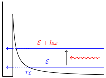
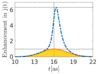


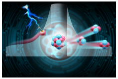



$\mathfrak{E} \geq \mathcal{O}(10^{16}\text{V/m})$ dynamically assisted nuclear fusion

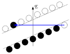


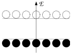





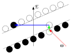
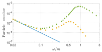


$\mathfrak{E} \geq \mathcal{O}(10^{17}\text{V/m})$ dynamically assisted Sauter-Schwinger pair creation







Pump & probe fields

N. Ahmadiniaz, T.E. Cowan, R. Sauerbrey, U. Schramm, H.-P. Schlenvoigt, R.S., Phys. Rev. D **101**, 116019 (2020)

pump field (polarizes vacuum)		
magnetic field	laser focus	nuclear Coulomb field
$\mathcal{O}(10^{-9}\mathfrak{B}_{\text{crit}})$	$\mathcal{O}(10^{-4}\mathfrak{E}_{\text{crit}})$	$\mathcal{O}(\mathfrak{E}_{\text{crit}})$
$\delta n = \mathcal{O}(10^{-22})$	$\delta n = \mathcal{O}(10^{-11})$	$\delta n = \mathcal{O}(10^{-2})$
field strength $\rightarrow$		$\leftarrow$ interaction volume
probe field (detects vacuum polarization)		
optical laser	XFEL	γ-ray
$\mathcal{O}(\text{eV})$	$\mathcal{O}(\text{keV})$	$\mathcal{O}(\text{MeV})$
$N = \mathcal{O}(10^{20})$	$N = \mathcal{O}(10^{12})$	$N = \mathcal{O}(1)$
wavenumber $\rightarrow$		$\leftarrow$ photon number
PVLAS, BMV, ...	HIBEF	Delbrück (ATLAS)

N. Ahmadiniaz, M. Bussmann, T.E. Cowan, A. Debus, T. Kluge, R.S., Phys. Rev. D Lett. **104**, 011902 (2021)