Extremely high-intensity laser interactions with fundamental quantum systems

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Outline

Laser-Vacuum Interaction: laser-enhanced vacuum fluctuations and refractivity

Laser-Electron Interaction: Relat. quantum dynamics, Pair creation & recolliders

Laser-Ion and Nuclei Interaction: Ionic and Nuclear Quantum Optics via XFEL

Applications: characterising laser pulses, metrology, proton therapy, laser colliders, laboratory astrophysics

Quantum Vacuum & Critical fields

- Virtual particles are present
- They live for a very short time and cover a very short distance ($\tau=\hbar/mc^2$ and $\lambda_c=\hbar/mc$, respectively). For electrons and positrons: $\lambda_c\approx10^{-11}$ and $\tau\approx10^{-21}$s.

Critical fields: physical meaning

$$\frac{\hbar}{mc} \times eE_{cr} \sim mc^2$$
$$\frac{e\hbar}{mc} \times B_{cr} \sim mc^2$$

Available in highly charged ions but not feasible in near future with laser

$$I_{cr} = \frac{cE_{cr}^2}{8\pi} = 2.3 \times 10^{29} \text{ W/mc}^2$$

Effects for much smaller fields?
Quantum Vacuum: Real and Virtual Pairs

Dirac dynamics of an electron with negative energy in crossed laser beams: pairs from $10^{26}$ W/cm$^2$ approaching critical field $mc^2/\hbar$
Regimes of QED in a strong laser field

A particle ($e^-, e^+$ or $\gamma$) with energy $E (\hbar \omega$ for a photon) collides head on with a plane wave with amplitude $E_L$ and angular frequency $\omega_L$ (wavelength $\lambda_L$)

Relevant parameters (Di Piazza et al., RMP 84, 1177 (2012)):

$$\xi = \frac{1}{2\pi} \frac{|e| E_L \lambda_L}{m c^2} = \frac{|e| E_L \lambda_c}{\hbar \omega_L}$$

$$\chi = 2 \frac{\hbar \omega}{mc^2 E_{cr}} = \left| \frac{E_L}{E_{cr}} \right|$$

Multiphoton effects
Relativistic effects
Quantum effects (photon recoil, pair production)

Strong-field QED regime

Courtesy Di Piazza
Optical laser and electron accelerator technology

<table>
<thead>
<tr>
<th>Optical laser technology ($\hbar\omega_L = 1$ eV)</th>
<th>Energy (J)</th>
<th>Pulse duration (fs)</th>
<th>Spot radius ($\mu$m)</th>
<th>Intensity (W/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>State-of-art (Yanovsky et al., Opt. Express (2008))</td>
<td>10</td>
<td>30</td>
<td>1</td>
<td>2x10^{22}</td>
</tr>
<tr>
<td>Soon (APOLLON, Vulcan, AstraGemini, BELLA etc...)</td>
<td>10-100</td>
<td>10-100</td>
<td>1</td>
<td>10^{22-10^{23}}</td>
</tr>
<tr>
<td>Near future (2020) (ELI, HiPER)</td>
<td>10^{4}</td>
<td>10</td>
<td>1</td>
<td>10^{25-10^{26}}</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Electron accelerator technology</th>
<th>Energy (GeV)</th>
<th>Beam duration (fs)</th>
<th>Spot radius ($\mu$m)</th>
<th>Number of electrons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional accelerators (PDG)</td>
<td>10-50</td>
<td>10^{3-10^{4}}</td>
<td>10-100</td>
<td>10^{10-10^{11}}</td>
</tr>
<tr>
<td>Laser-plasma accelerators (e.g. Leemans et al., PRL 2013)</td>
<td>0.1-5</td>
<td>50</td>
<td>5</td>
<td>10^{9-10^{10}}</td>
</tr>
</tbody>
</table>

$\xi = 7.5 \frac{\sqrt{I_L[10^{20} W/cm^2]}}{\hbar\omega_L[\text{eV}]}$

$\chi = 5.9 \times 10^{-2} \varepsilon[\text{GeV}] \sqrt{I_L[10^{20} W/cm^2]}$

Present technology allows in principle the experimental investigation of strong-field QED and laser particle physics

Courtesy Antonino Di Piazza
Effects to think of e.g. ….

- *Harmonic generation* in vacuum in the collision of two strong laser beams

- Vacuum *refractive indices* with phase shifts in the presence of a strong standing wave
In the presence of strong fields the Maxwell Lagrangian density has to be modified to take into account vacuum fluctuations.

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

Effects of vacuum fluctuations for realistic laser intensities?

Probe field polarization and ellipticity before and after interaction with intense field

• Strong field’s parameters: 10 PW, 800 nm, 30 fs, focused to one wavelength (intensity $10^{24}$ W/cm$^2$)
• Weak field’s parameters: 100 TW, 527 nm, 100 fs focused to 290 μm (intensity $7.5 \times 10^{16}$ W/cm$^2$)
• Separation between the two strong beams: 64 μm
• The position of the x in the figure corresponds to the classical formula: $(n+1/2)\lambda_p = D \sin \phi$
• With the above parameters one obtains about 6.4 diffracted photons per shot

Single charged particle quantum dynamics

Dirac Equation

\[ i\hbar \partial_t \Psi = \left\{ c\alpha \cdot \left[ p + \frac{e}{c} A \right] + \beta mc^2 + V \right\} \Psi \]

Laser-Driven Atoms: solved numerically in few groups since 1997

Alternatives: Klein Gordon (W.Becker, Faisal, Reiss), Schrödinger beyond Dipol, Expansions of Dirac Eq., Classical/Semiclassical Approaches;

\[ \frac{d}{dt} \vec{p} = m \frac{d}{dt} \frac{\dot{\vec{r}}}{\sqrt{1 - (\dot{\vec{r}}/c)^2}} = \vec{F}_{\text{Laser}} + \vec{F}_{\text{Coulomb}} \]
Nonresonant Laser-Particle/Ion Interaction:
Dirac Eq. for laser driven atomic systems


- Problems:
  - Dirac very similar to Schrödinger, but
    \[ \Delta t_{\text{Dirac}} \approx 10^{-5} \text{a.u.} \ll \Delta t_{\text{Schrödinger}} \approx 10^{-3} \text{a.u.} \]
- Solutions:
  - "Moving position space grid" to keep the grid size small
  - "Moving momentum space grid" to keep the position space grid resolution small
  - "Variably-sized position space grid" to dynamically adapt the grid size to requirements

\[ \Delta x_{\text{pol}} = \frac{2E_0}{\omega^2}, \quad \Delta x_{\text{prop}} = \frac{\pi E_0^2}{2c \omega^3} \]
Bound electrons and ionisation from highly charged ions

Directions and yields of ionisation are characteristic for laser intensity and ionic charge

=> Sensitive means of measuring extremely intense laser intensities

Tunneling and the time in the classically forbidden barrier

Numerical Dirac Simulation:
- Ion with Z=90 in the tunneling regime =>
- Momentum shift and coordinate drift at the tunneling exit yielding a tunneling time

Electrons: Dirac dynamics in strong laser pulses

Example: electron double scattering via 2D solution of Dirac equation

- Drift in laser-propagation direction via magnetic field component - problem for recollisions

- Enhanced quantum spreading with increased laser intensity & quantum interference at scattering processes

- Dirac propagation time consuming enhanced via adaptive grids

- Quantum features in various situations of relevance
Intrinsic quantum effects: Spin dynamics & QED for electron-laser scattering

Scattering of electron at crossed laser fields with spin flip (Kapitza-Dirac effect) via propagation of Dirac equation involving laser fields

A full QED approach reveals quantum nature of the laser field: collapse and revivals for spin oscillations as magnetic coupling weak even for rather intense laser pulses of about $10^{18}$ W/cm$^2$

Multiphoton Compton scattering is one of the most fundamental processes in electrodynamics. The electron exchanges many photons with the laser field and emits a high-energy photon. The quantum photon-energy spectrum with sharp cut-off reduces to the classical one at $\hbar \omega_1$ (see also Seipt and Kaempfer, PRA 2011, Boca and Oprea, Phys Scr. 2011).
Radiative reaction

\[ m_0 \frac{d\mathbf{u}^\mu}{ds} = -e F_T^{\mu\nu} \mathbf{u}_\nu \]

\[ \partial_\mu F_T^{\mu\nu} = -e \int ds \delta(x - x(s)) \mathbf{u}^\nu \]

\[ F_T^{\mu\nu}(x) = F^{\mu\nu}(x) + F_S^{\mu\nu}(x) \]

Feed-back of modified fields yields Lorentz-Abraham-Dirac equation.

- In the realm of classical electrodynamics, i.e. if quantum effects are negligible, the Lorentz-Abraham-Dirac equation can be approximated by the so-called Landau-Lifshitz equation (Landau and Lifshitz, 1947; Spohn, Europhys. Lett. 2000; Gralla et al., Phys. Rev. D 2009)

Damping & Reabsorption of initially emitted Light alters Dynamics

first with lasers in JPB 31, L75 (1998)
Radiation reaction effects of electrons in plasma

Radiation reaction (RR) is expected to play a relevant role in the interaction between an intense ($\sim 10^{23}$ W/cm$^2$) laser beam and a plasma.

Strong laser beam interacting with a plasma slab: RR effects on the energy spectrum & for generation of forward Raman scattering

The effects of RR have been taken into account by including in the particle in cell code new force terms according to the one-particle Landau-Lifshitz equation.

Laser and plasma parameters:
- Wavelength $\lambda = 0.8$ $\mu$m,
- Intensity $I = 2.33 \times 10^{23}$ W/cm$^2$,
- Laser pulse duration 7 cycles,
- Plasma density $n = 100n_c$,
- Plasma thickness $1\lambda$.


Instabilities in plasmas may be enhanced via radiative reaction


RR effects for linear polarization strongly narrow the ion spectrum
Pair production in strong laser pulses

Historical Remark: SLAC Experiment
The first laboratory evidence of multiphoton pair production.

- $3.6 \times 10^{18} \, W/cm^2$ optical laser (2.35 eV)
- Electron accelerated to 46.6 GeV
- Energy threshold reached (in center of inertial frame)

Theory: combined treatment of two processes

**direct:** $e + N\omega \rightarrow e' + e^+e^-$

**Bethe-Heitler type**

**two-step:**

$e + \omega \rightarrow e' + \gamma$

$\gamma + N\omega \rightarrow e^+e^-$

Separate Direct and Two-Step Processes

Direct process and two-step process can be separated by kinematic requirements at VUV intensities $10^{13} \text{ W/cm}^2$ with a 17.5 GeV electron from DESY beamline.

- Substantial pair production rate in various interaction regimes
- Novel usage of DESY beamline (17.5 GeV) for pair production
- The future of pair production: all-optical setup

Electron-positron pair production: Mechanisms

Three main classes of pair-production processes have been investigated, including laser fields:

- **Laser-photon collision (a)**: \( \kappa = \frac{2 \omega}{m} \left( \frac{E_L}{E_{cr}} \right) \)
  \[ \sim m \kappa^{3/2} \exp\left(-\frac{8}{3} \kappa\right) \]

- **Laser-charge collision (b)**: \( \chi = \frac{2 \epsilon}{m} \left( \frac{E_L}{E_{cr}} \right) \)
  \[ \sim m (Z \alpha)^2 \exp\left(-\frac{30.52}{\chi}\right) \]

- **Laser-laser collision (c)**: \( \Upsilon = \frac{E_L}{E_{cr}} \)
  \[ \sim m \Upsilon^2 \exp\left(-\frac{\pi}{\Upsilon}\right) \]

e.g. Schützhold et al PRL 2009 - Hu et al PRL 2010 - Ruf et al PRL 2009

perturbative multiphoton regime at \( \xi \gg 1 \) and non-perturbative tunneling regime at \( \xi \gg 1 \) – see also Di Piazza et al, RMP 2012 or arXiv 2012
Lab. astrophysics: Positron Jets with lasers

Theory support for experimental campaign carried out at the HERCULES laser (CUOS, Michigan) with teams around G. Sarri, K. Krushelnick & M. Zepf

(a) Table-top experimental setup for the production of short, narrow, and ultra-relativistic positron beams. (c) 30 fs positron jets as recorded by the image plate.

(b) Our theoretical analysis revealed that the scaling with the charge number $Z$ and the thickness $d$ is consistent with a two-step process (Bremsstrahlung+Bethe-Heitler)
Parameters & possible astrophysical significance

An ultrashort (30fs), ultra-collimated (3mrad) high energy ($E_{\text{MAX}} = 150$ MeV) positron beam generated.

Overall positron yield: $3 \times 10^7$
Overall lepton yield: $3 \times 10^8$
Positron density: $2 \times 10^{14}$ cm$^{-3}$
Lepton density: $2 \times 10^{15}$ cm$^{-3}$
Intensity: $10^{19}$ erg s$^{-1}$ cm


In a subsequent experimental campaign at Astra Gemini (Oxford) with our theory support ultra-relativistic neutral electron-positron beams have been generated (G. Sarri, et al., Nature Comm. 6, 4767 (2015))

Parameter not as in astrophysical jets but with scaling results may become relevant

Generation of $e^-/e^+$ jets with variable % of $e^+$ from 0 to 50%!
Plasma dynamics of those neutral lepton- antilepton jets yet to be studied
Particle Physics with Strong Lasers

Positronium dynamics in an intense laser field:

Particle reactions by laser-driven $e^+e^-$ collisions

**Energetic threshold for muon:**

$$2eA \geq 2Mc^2$$

($I \geq 5 \times 10^{22} \text{ W/cm}^2$ at $\lambda = 1 \mu\text{m}$)

Theory of laser-driven muon creation

Employ Volkov states in the usual amplitude for $e^+e^- \rightarrow m^+m^-$:

$$S_{e^+e^-\rightarrow\mu^+\mu^-} = -i\alpha \int d^4x \, d^4y \, \overline{\Psi}_{p_+}(x) \gamma^\mu \Psi_{p_-}(x)$$
$$\times D_{\mu\nu}(x-y) \overline{\Psi}_{p_-}(y) \gamma^\nu \Psi_{p_+}(y)$$

Average over the momentum distribution in the Ps ground state:

$$S_{Ps\rightarrow\mu^+\mu^-} = \int \frac{d^3p}{(2\pi)^3} \Phi(p) \, S_{e^+e^-\rightarrow\mu^+\mu^-}$$
Muon pair creation in XFEL-nucleus collisions

- Relativistic Doppler shift leads to $\hbar \omega' = (1+\beta)\gamma \hbar \omega = 168$ MeV in nuclear rest frame

- Energy threshold $\Delta \varepsilon = 2Mc^2 = 211$ MeV for $\mu^+\mu^-$ creation can be overcome by absorption of two x-ray photons

For ion beam with $10^{11}$ particles and XFEL pulse with 100 fs, 40 kHz and $10^{22}$ W/ cm$^2$ => 1 muon pair per second envisaged

C. Müller et al, PRL 101, 060402 (08) and, Phys. Lett. B 672, 56 (09)
Higgs boson creation in laser-boosted lepton collisions

From Collisions to Recollisions in Vacuum

Recollisions in atomic physics: Semi-classical three-step model for High-harmonics generation (HHG)

As the free electron is accelerated by the laser field, a large amount of energy is released during the recollision.

see e.g. P. Corkum (1993) or M. Protopapas et al, Rep. Prog. Phys. (1997)
Recollisions of laser-generated electron-positron pairs

Quasistatic vs. recollision contribution

- The Polarization operator mainly describes vacuum fluctuations (annihilation of the pair within one formation length, yellow curve)
- If real pair creation becomes sizable ($\chi = 1$), also recollision processes contribute (red curve)
- They are responsible for the large plateau region in the photon absorption spectrum

Scaling of the plateau region

- During a recollision many laser photons can be efficiently absorbed from the laser
- The width of the plateau scales as $3.17\xi^3/\chi$
- The height of $|\int P_{\perp}|^2$ scales as $\chi^{10/3}/\xi^6$
- The recollision probability is suppressed for parallel photon polarization (light colors), as the momentum distribution hinders recollisions

Ions interacting with high frequency lasers: laboratory astrophysics

Iron (Fe): the most visible (even if not the most abundant) element of the universe. Fe ions in stars emit x-ray radiation with characteristic frequencies.

E.g. x-ray spectrum of the star system Capella (in the constellation Auriga), recorded by the Chandra X-ray Observatory:

Data: D. P. Huenemoerder et al., Astron. J. 141, 129 (2011)
Figure: S. Bernitt, et al., Nature 492, 225 (2012)
**Problem:** observed lines carry information about the plasma and correlated bound electron dynamics

**Alternative**

x-ray laser spectroscopy with Fe ions trapped in an EBIT by the group Crespo/Ullrich (at LCLS free electron laser facility)
i.e. avoiding plasma influence

Compare with theory:
- 3C: $1s^22s^2(2p^5)_{1/2}3d_{3/2}$
- 3D: $1s^22s^2(2p^5)_{3/2}3d_{5/2}$

large-scale multiconfiguration Dirac-Fock

Theoretical **prediction** for the brightness of the 3C line 30% above the measured value by x-ray laser spectroscopy, also ratio still incorrect: i.e. plasma influence in the modelling not only responsible for discrepancy between experiment and theory!
PRL 2014 shows that nonlinear interaction need be included in astrophysical models

N. S. Oreskina *et al.*, PRL 113, 143001 (2014)
Highly charged ions in high-frequency light (XFEL or via ELI): population transfer and application in high-precision metrology

Transition data – transition energies and matrix elements - for highly charged ions are required for the modeling of astrophysical or thermonuclear fusion plasmas

**Resonance fluorescence:** excitation by a resonant laser field (XFEL) + spontaneous decay

Line widths can be largely decreased by an additional optical driving: a new tool to measure the **transition matrix elements** of HCI via the separation of the spectral lines given by the Rabi frequency

Fluorescence photon spectrum for the 2s-2p_{3/2} transition in lithiumlike $^{209}$Bi (Z=83). Red dashed line: the broad spectrum with x-ray driving between levels 1 and 3 (panel a). Blue line: the narrowed spectrum when an optical laser driving between the hyperfine-split levels 1 and 2 is switched on in addition (panel b)

1. Preparation of the system

- An x-ray pulse driving the $1 \leftrightarrow 2$ transition and a subsequent laser pulse driving the $2 \leftrightarrow 3$ transition prepare the system in the initial, slowly decaying state.

- An optical-frequency-comb laser consisting of a train of $2\pi$ pulses imprints a pulse-like structure in the x-ray dipole response with increased effective decay time.

2. Optical-frequency-comb control and resulting x-ray dipole response
Nuclear Quantum Optics with XFEL: Rabi flopping

- resonant laser-nucleus interaction allows to induce Rabi flopping of nuclear population
- detection e.g. via scattered light, state-selective measurements
- potential application: model-free determination of nuclear parameters

example nuclei:

<table>
<thead>
<tr>
<th>nucleus</th>
<th>transition</th>
<th>$\Delta E$ [keV]</th>
<th>$\mu$ [e fm]</th>
<th>$\tau(g)$</th>
<th>$\tau(e)$ [ps]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{153}$Sm</td>
<td>$3/2^-$ $\rightarrow$ $3/2^+$</td>
<td>35.8</td>
<td>$&gt;0.75^{(1)}$</td>
<td>47 h</td>
<td>$&lt;100$</td>
</tr>
<tr>
<td>$^{181}$Ta</td>
<td>$9/2^-$ $\rightarrow$ $7/2^+$</td>
<td>6.2</td>
<td>$0.04^{(1)}$</td>
<td>stable</td>
<td>$6 \cdot 10^6$</td>
</tr>
<tr>
<td>$^{225}$Ac</td>
<td>$3/2^+ $ $\rightarrow$ $3/2^-$</td>
<td>40.1</td>
<td>$0.24^{(1)}$</td>
<td>10.0 d</td>
<td>720</td>
</tr>
<tr>
<td>$^{223}$Ra</td>
<td>$3/2^-$ $\rightarrow$ $3/2^+$</td>
<td>50.1</td>
<td>0.12</td>
<td>11.435 d</td>
<td>730</td>
</tr>
<tr>
<td>$^{227}$Th</td>
<td>$3/2^-$ $\rightarrow$ $1/2^+$</td>
<td>37.9</td>
<td>$\cdots^{(2)}$</td>
<td>18.68 d</td>
<td>$\cdots^{(2)}$</td>
</tr>
<tr>
<td>$^{231}$Th</td>
<td>$5/2^-$ $\rightarrow$ $5/2^+$</td>
<td>186</td>
<td>0.017</td>
<td>25.52 h</td>
<td>1030</td>
</tr>
</tbody>
</table>

Population inversion in $^{223}$Ra for laser parameters as in the DESY TESLA technical design report supplement

Nuclei: population transfer

Parameters for XFEL but alternative via oscillating mirrors at ELI (D van der Brugge and A. Pukhov, Phys. Plasmas 17, 033110 (2010), A. M. Sergeev et al., Proc. SPIE 8080, 808017 (2011))

\[ |D\rangle = \frac{\Omega_s}{\sqrt{\Omega_p^2 + \Omega_s^2}} |1\rangle - \frac{\Omega_p}{\sqrt{\Omega_p^2 + \Omega_s^2}} |2\rangle \]

Nuclear quantum dynamics and isomer triggering

**Nuclear isomer** = nucleus in long-lived excited state

- Lifetimes: ns, μs, ms, s, min, h, years, …

**Triggering** = release of stored excitation energy on demand

- clean energy source (nuclear battery)
- insight in nuclear structure
- possibly astrophysical significance

References:

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**$^{93}$Mo nucleus**

<table>
<thead>
<tr>
<th>Level</th>
<th>Energy (keV)</th>
<th>Decay Path</th>
</tr>
</thead>
<tbody>
<tr>
<td>$17/2^+$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$21/2^+$</td>
<td>2429.80</td>
<td></td>
</tr>
<tr>
<td>$13/2^+$</td>
<td>2424.95</td>
<td></td>
</tr>
<tr>
<td>$5/2^+$</td>
<td>2161.90</td>
<td></td>
</tr>
<tr>
<td>$2161.90$ keV</td>
<td>intermediate</td>
<td></td>
</tr>
<tr>
<td>$2429.80$ keV</td>
<td>triggering</td>
<td></td>
</tr>
<tr>
<td>$2424.95$ keV</td>
<td>isomeric state</td>
<td></td>
</tr>
<tr>
<td>$0$ keV</td>
<td>ground state</td>
<td></td>
</tr>
</tbody>
</table>

$E_2$ decay cascade

$1$ MeV photon = signature for triggering

4.85 keV accessible by lasers (XFEL)
Mechanisms of laser-nucleus interaction in embedded nuclei

Direct laser-nucleus interaction:

- XFEL provides x-rays (< 25 keV) resonant with nuclear transition
- Obstacles:
  - small nuclear transition widths
  - small size of nuclei
  - screening from electrons

Secondary nuclear processes:

- High intensity XFEL can produce new states of matter, like cold, high-density plasmas
- Processes coupled to the atomic shell, like NEEC become possible
- NEEC is time-reversal of internal conversion

Competition between **direct photoexcitation** and **secondary NEEC**
Results: $^{93}\text{mMo}$ triggering with the XFEL

Direct photoexcitation:

- XFEL on resonance with triggering transition (4.85 keV)
- Consider realistic laser parameters, e.g.: LCLS at SLAC

Number of triggered isomers per pulse: $\sim 1.8 \times 10^{-15}$

- Spatial coherence can drastically increase nuclear triggering (see XFEL oscillator)

Secondary NEEC:

- NEEC prefers capture into deep vacancies
- Broad electron distribution present

Number of triggered isomers per pulse:
$\sim 5.6 \times 10^{-9}$ ($T_e = 350$ eV)

- NEEC takes place on longer time scale compared to laser pulse
- Many NEEC resonance channels can contribute


FIG: Number of triggered isomers after a single pulse. Comparison between photoexcitation and secondary NEEC.
Tunneling rate is barely influenced by a strong optical laser (800 nm) BUT:

alpha particle spectrum is completely changed by the laser

Recollisions with the daughter nucleus occur at intensities of $10^{22}$-$10^{23}$ W/cm$^2$

X-ray quantum optics with nuclei in solids

$^{57}$Fe Mössbauer nucleus in nm-sized planar cavity

$$J_0 = 3/2$$

$$J_0 = 1/2$$

$$\lambda = 0.86 \ \text{Å}$$
$$\hbar \omega_0 = 14.4 \text{ keV}$$
$$\hbar \Gamma = 4.7 \times 10^{-9} \text{ eV}$$
$$1/\Gamma = 141 \text{ ns}$$

Typical experimental setup at synchrotron radiation source

Spectral control with Mössbauer nuclei

Operate cavity as x-ray interferometry

Continuum: broadband cavity reflection
Bound state: narrow nuclear response
Relative phase controlled by x-ray incidence angle

Demonstration of nuclear coherences, interferences and enhanced x-ray refractivity
Kilian Heeg et al (Evers group) PRLs 2013 & twice 2015
see also recent Science/ Natures by Röhlsberger & Kocharovskaya groups
Conclusions

**Laser-vacuum interaction:** light-light scattering, vacuum refractivity, matterless double slit & multi slits

**Laser-electron interaction:** Dirac & spin dynamics, pair creation with created jets for astrophysics, particle physics

**Laser-ion & nuclei interaction:** metrology and tunneling times, nuclear population transfer, astrophysics iron spectra
Quantum optics with Mössbauer nuclei

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Kilian Heeg et al (Evers group) PRLS 2013, twice 2015
see also recent Science/ Natures by Röhlsberger & Kocharovskaya groups
**Recollisions of laser-generated electron-positron pairs**

Classical trajectories (laser polarization direction) of electrons created shortly after a laser-field peak (positron trajectories have an opposite sign). Color: energy gain at the recollision point.

- Already for existing laser parameters ($\xi = 100$) pair-production probabilities of 10% are reached for a single GeV photon. [arXiv:1406.7235](https://arxiv.org/abs/1406.7235) S. Meuren et al PRD 2015

- After its creation the electron-positron pair propagates in the field.
- For a linearly polarized laser the two particles may recollide.
- We have shown quantum-mechanically that these processes contribute to the polarization operator (photon propagator with electron-positron loop): 

\[
q_2^\mu = q_1^\mu + n k^\mu 
\]

MeV Acceleration and Nuclear Physics via Laser-Plasma Interaction


Spontaneously generated x-ray coherences

Interaction with vacuum can “spontaneously” generate coherences

SGC usually suppressed, e.g. for atoms in free space → experimentally unexplored

We observed nuclear SGC by engineering an anisotropic vacuum with only one polarization

Signature: destructive interference in spectrum

Data shows: Essentially no decoherence

SGC can appear if atoms experience anisotropic environments

Nuclear control experimentally? - first atoms via Fano resonances

- Recall attosecond spectroscopy experiment in T. Pfeifer's group @ MPIK
- Two pathways for ionisation due to autoionising state in He
- Manipulate interference between “bound state” and “continuum” channel via control laser field which imprints phase shift on atoms

Control of spectroscopic line shapes

![Diagrams showing the process of nuclear control experimentally](image-url)
Coherence based population transfer

\[ |D\rangle = \frac{\Omega_s}{\sqrt{\Omega_p^2 + \Omega_s^2}} |1\rangle - \frac{\Omega_p}{\sqrt{\Omega_p^2 + \Omega_s^2}} |2\rangle \]

• One can see that if the initial longitudinal momentum of the electron is almost compensated by the laser field, the resulting angular distribution of the emitted radiation is very sensitive to radiation reaction.

• Numerical parameters: electron energy 40 MeV, laser wavelength 0.8 μm, laser intensity $5 \times 10^{22}$ W/cm$^2$, focused to 2.5 μm (10 PW), pulse duration 30 fs.

Test of Landau Lifshitz equation envisaged.. A. Di Piazza et al, PRL 102, 254802 (2009)
QED cascades

By an avalanche or cascade process we mean here a process in which even a single electron in a field emits high-energy photons, which can interact with the field itself generating electron-positron pairs, which, in turn, emit photons again and so on (a cascade process may also be initiated by a photon rather than by an electron) - Figure courtesy Elkina.

- Kirk and Bell, Phys. Rev. Lett. 2008: first prediction of a cascade production if even a single electron is present in the focus of a standing wave with intensity larger than $10^{24}$ W/cm$^2$
- Bulanov et al., Phys. Rev. Lett. 2010): no upper limit is envisaged in the case of linear polarization, due to the reduced electromagnetic emission
(recall: cascade debate only for counterpropagting laser pulses)