Extremely high-intensity laser interactions with fundamental quantum systems

Christoph H. Keitel, Max Planck Institute for Nuclear Physics (MPIK)

involved key group members in presented projects:
A. Di Piazza, J. Evers, Z Harman, K. Z. Hatsagortsyan, C. Müller, A Palffy
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, G. V. Brown, J. K. Rudolph, et al., Nature 492, 225 (2012)
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!
Experimental campaign carried out at the HERCULES laser (CUOS, Michigan)

Second example: Pair production with lasers

- Primary electron beam $\theta = 5$ mrad, $E_{\text{MAX}} = 200$ MeV
- 3mm gas-jet 5.5 bar He with 2.5% N$_2$
- 0.8 J, 30fs, $6 \times 10^{18}$ W cm$^{-2}$
- 2 - 6 mm (Ta, Pb, Sn, Cu)
- positron beam detected by IP after 0.8T, 15 cm magnet
An ultrashort (30fs), ultra-collimated (3mrad) high energy ($E_{\text{MAX}} = 150$ MeV) positron beam was generated.

The beam co-travels with an electron beam and with a burst of gamma-rays.

Total number of positrons of $10^7$. 
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
Divergence: 3 mrad

G. Sarri et al., submitted (2013), arXiv 1304.5379
Outline

Laser-Vacuum Interaction: laser-enhanced vacuum fluctuations, refractivity and matterless double slits

Laser-Electron Interaction: Radiative Reaction, Pair creation, Laser Colliders & Laser Particle Physics

Laser-Ion and Nuclei Interaction: Laser acceleration & Radiation, Nuclear Quantum Optics

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

Quantum Vacuum & Critical fields

- Virtual particles are present
- They live for a very short time and cover a very short distance ($\tau = \frac{\hbar}{mc^2}$ and $\lambda_c = \frac{\hbar}{mc}$, respectively). For electrons and positrons: $\lambda_c \approx 10^{-11}$ cm and $\tau \approx 10^{-21}$ s.

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

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

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/cm² approaching critical el. field $m^2c^2/\hbar^2$
Regimes of QED in a strong laser field

A particle (mm⁻, mm⁺ or 15) with energy E (•• for a photon) collides head on with a plane wave with amplitude □ and angular frequency • (wavelength Ⅲ•)

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

\[ \xi = \frac{1}{2\pi} \frac{|e|E_L\lambda_L}{mc^2} = \frac{|e|E_L\lambda_C}{\hbar\omega_L} \]

\[ \chi = \frac{2\hbar\omega}{mc^2} \frac{E_L}{E_{cr}} = \frac{E_L}{E_{cr}} \left|\text{r.f.}\right.\]

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure.png}
\caption{Strong-field QED regime}
\end{figure}

Courtesy Di Piazza
Optical laser and electron accelerator technology

<table>
<thead>
<tr>
<th>Optical laser technology ((\hbar \omega_L = 1 \text{ eV}))</th>
<th>Energy (J)</th>
<th>Pulse duration (fs)</th>
<th>Spot radius ((\lambda \nu ))</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>(2\xi 10^{22})</td>
</tr>
<tr>
<td>Soon (2013) (APOLLON, Vulcan, Astra-Gemini, 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 ((\lambda \nu ))</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 (Leemans et al., Nature. Phys. 2006)</td>
<td>0.1(¥1)</td>
<td>50</td>
<td>5</td>
<td>(10^9)(¥10^{10})</td>
</tr>
</tbody>
</table>

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

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

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

Diffraction is a well known phenomenon in optics.

Due to vacuum polarization effects, a strong focused standing wave can "diffract" an X-ray probe.
Vacuum index of refraction: X-rays interact with strong standing wave

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

- Current \( J(r,t) \) arises in wave eq. because of vacuum fluctuation effects
- \( J(r,t) \) is proportional to \( E^3/(E_{cr})^2 \) with \( E_{cr} = m^2c^3/\hbar e = 1.3 \times 10^{16} \text{ V/cm} \)
- Generally speaking vacuum corrections are of the order of \( (E/E_{cr})^2 << 1 \)
Results with diffraction:

Probes polarization before the interaction

Strong beam: $I_0=10^{23}$ W/cm$^2$, $w_0=\lambda_0=0.745$ μm

Probe beam: $\lambda_p=0.4$ nm, $w_p=8$ μm

It results: $\xi_x=0.14/(y[\text{cm}])$, $\xi_z=16/(y[\text{cm}])$

- $\psi$ and $\varepsilon$ depend on the observation distance $y_d$
- The PVLAS expected ellipticities were $\approx 5 \times 10^{-11}$ rad
- The refractive index approach predicts $\psi=0$ and $\varepsilon\approx 4 \times 10^{-7}$ rad (diffraction effects are important!)
- Problems because of low photon statistics can be compensated for with an X-FEL as a probe and a strong field with $I_0=10^{25}-10^{26}$ W/cm$^2$


**Stimulated photon-photon scattering**

Electron-positron fluctuations can mediate a pure quantum interaction among laser beams in the vacuum in numerous ways

- Multi PW-class laser systems may open the possibility of observing for the first time either direct photon-photon scattering in vacuum (Lundstroem et al. Phys. Rev. Lett. 2006)
A matterless double-slit via vacuum fluctuations

Laser enhanced vacuum fluctuations for a fundamental scenario: double slit set-up having been essential for our understanding of quantum mechanics

All double-slit schemes investigated so far have involved matter (either the particles employed like electrons, neutrons etc. or the slits): here only via light-light interaction
- 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

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

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; QED, Nuclear and High-energy Approaches

\[ \frac{d}{dt} \vec{p} = m \frac{d}{dt} \frac{\vec{r}}{\sqrt{1 - (\vec{r}/c)^2}} = \vec{F}_{\text{Laser}} + \vec{F}_{\text{Coulomb}} \]

\[ \mathcal{L} = \frac{1}{2} (E^2 - B^2) + \frac{2\alpha^2}{45m^4} \left[ (E^2 - B^2)^2 + 7(E \cdot B)^2 \right] \]
Electrons: Dirac dynamics of charged particles in strong laser fields

Free Electron

Analytical for planes waves
Volkov 1932

E = 640 a.u., w = 8 a.u., kin Energie ca. 40 keV

Movie G. Mocken
• Problems:

• Dirac very similar to Schrödinger, but

\[ \Delta t_{\text{Dirac}} \approx 10^{-5} \text{a.u.} \ll \Delta t_{\text{Schrödinger}} \approx 10^{-3} \text{a.u.} \]

• Relativistic laser parameters \( E_0 / \omega >> 1 \) require
  • large grids

\[ \Delta x_{\text{pol}} = \frac{2E_0}{\omega^2}, \quad \Delta x_{\text{prop}} = \frac{\pi E_0^2}{2c \omega^3} \]

  • high resolution (n x n points)

  • many integration steps (m) per cycle

Time requirements \( \sim m n^2 \log n \)

• 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

Bound electrons: Ionisation & Characterising intense pulses with highly charged ions

Directions and yields of ionisation are characteristic for laser intensity and ionic charge => Sensitive means of measuring extremely intense laser intensities


- increasing laser intensity -

Tunneling Regime

**Numerical Dirac Simulation:**
- ion with \( Z = 90 \) in the tunneling regime
- momentum shift and coordinate drift at the tunneling exit yielding a tunneling time

M. Klaiber et al, PRL 2013
MeV harmonics & zeptosecond γ-ray pulses & beyond

alternatives via overdense plasmas (S. Gordienko et al., PRL 93, 115002(2004))
Thomson backscattering (P. Lan et al, PRE 066501(2005))
and yoctosecond photon pulses via quark-gluon plasmas (with double-peak for pump-probe)

Multiphoton Compton scattering

- 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 $\xi \approx 1$ (see also Seipt and Kaempfer, PRA 2011, Boca and Oprea, Phys Scr. 2011)
Photon merging in laser-proton collisions

Multiphoton Thomson scattering (laser photons are merged by the proton charge)

Laser-photon merging (laser photons are merged by the virtual electron-positron pairs)
Spin dynamics in the Kapitza-Dirac effect

Spinflip for odd photon numbers

- 3-photon Kapitza-Dirac effect (2 absorbed, 1 emitted)

Bragg condition must be fulfilled

- $k$ or $p_E$ must be relativistic

Counterpropagating laser beams:
- Peak intensity: $2 \cdot 10^{23}$ W/cm² (each beam)
- Wave length: 0.4 nm (photons)

Electron beam:
- Momentum: 176 keV/c
- Inclination: $\theta = 0.4^\circ$

Time of half Rabi cycle: 1 fs

Collapse-and-revival dynamics of strongly laser-driven electrons

FIG. 1. Electron motion in a single-mode quantized field. $p_0$ is the initial momentum of the electron, $b$ is the polarization vector of the field, the $z$ axis is directed along the wave vector $k$, $a$ and $a^\dagger$ are, respectively, the annihilation and creation operators, $\omega$ is the frequency of the field, and $N_+(N_-)$ is the number of particles with helicity equal to 1 ($-1$).


FIG. 2. Probability of finding an electron with flipped polarization as a function of the angle $\theta$ for an intensity $I = 10^{18}$ W/cm$^2$, a laser frequency $\omega = 7.8 \times 10^4$ cm$^{-1}$, with a corresponding wavelength of 800 nm, an initial probability $p_{-1} = 0$, and $\gamma$ values of the electron equal to 5 and 10.
**Pair production in strong laser pulses**

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

- $3.6 \times 10^{18} \text{ W/cm}^2$ 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 $10^{13} \frac{W}{cm^2}$ 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:

a) Laser-photon collision (a)) $\Rightarrow (2!/m)(E_L/E_{cr}) \approx m^{3/2}\exp\left\{\frac{8}{3}\right\}$
b) Laser-charge collision (b)) $\Rightarrow (2E/m)(E_L/E_{cr}) \approx m(Z^2)\exp\left\{\frac{30.52}{\hat{A}}\right\}$
c) Laser-laser collision (c)) $\Rightarrow E_L/E_{cr} \approx \hat{A}^2\exp\left\{\frac{1/4}{\hat{A}}\right\}$

eg Schützhold et al PRL 2009 - Hu et al PRL 2010 - Ruf et al PRL 2009
perturbative multiphoton regime at $\gg 1$ and non-perturbative tunneling regime at $\gg \hat{A}$1 – see also Di Piazza et al, RMP 2012 or arXiv 2012

<table>
<thead>
<tr>
<th>Parameter (head-on collision)</th>
<th>Rate scaling (tunneling)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser-photon collision (a))</td>
<td>$m^{3/2}\exp\left{\frac{8}{3}\right}$</td>
</tr>
<tr>
<td>Laser-charge collision (b))</td>
<td>$m(Z^2)\exp\left{\frac{30.52}{\hat{A}}\right}$</td>
</tr>
<tr>
<td>Laser-laser collision (c))</td>
<td>$m^{2}\exp\left{\frac{1/4}{\hat{A}}\right}$</td>
</tr>
</tbody>
</table>
QED cascades

• In the E-144 experiment at SLAC only 100 positrons have been observed out of 22000 shots, each involving about $10^7$ electrons.

• Are there more efficient ways of producing positrons?

• 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 Elekina.

• Radiation-reaction effects prevent the development of a cascade in the collision of an electron/photon beam with a plane wave (Sokolov et al. Phys. Rev. Lett. 2010).
• 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 $10^{24} \text{ W/cm}^2$

• Idea: one of the laser beams acts as an accelerator for the electron that becomes ultrarelativistic and collides with the other beam

• This effect was exploited in (Fedotov et al., Phys. Rev. Lett. 2010) to show that an intrinsic upper limit should exist for a laser field amplitude given by $\mathcal{E}_\text{mgm}$ corresponding to an intensity $10^{25} \text{ W/cm}^2$

• This conclusion was questioned in (Bulanov et al., Phys. Rev. Lett. 2010), where no upper limit is envisaged in the case of linear polarization, due to the reduced electromagnetic emission

• Recent most detailed description of QED cascade formation in Nerush et al. Phys. Rev. Lett. 2011: cascades in laser-laser collision occurs independently on the laser polarization at intensities of the order of $10^{24} \text{ W/cm}^2$
Particle Physics with Strong Lasers

Positronium dynamics in an intense laser field:

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

- muon production ($m_\mu c^2 = 106$ MeV)
- pion production ($m_\pi c^2 = 140$ MeV)

Energetic threshold for muon: $2eA \geq 2Mc^2$

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


Also Pion Production via Proton Laser Collision: A Dadi & C Müller, Phys Lett B 697, 142 (2011)
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:

$$S_{Ps \rightarrow \mu^+ \mu^-} = \int \frac{d^3p}{(2\pi)^3} \Phi(p) \ S_{e^+ e^- \rightarrow \mu^+ \mu^-}$$
Total production rate  
(linear laser polarization)

Simple-man's model:
Total rate can be explained via the free cross-section $s$ and the $e^+e^-$ wave-packet spreading

$R_{Ps} \sim \frac{\sigma}{\xi(\alpha \xi \lambda)^3}$

Process observable at high Ps density ($10^{18} \, \text{cm}^{-3}$) and laser rep rate (1 Hz)

Solid line: analytical approximation  
Black squares: numerical results

Müller, Hatsagortsyan & Keitel,  
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 \( \Delta \varepsilon = 2Mc^2 = 211 \text{ MeV} \) 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 \( 10^{22} \text{ W/cm}^2 \)

\( \Rightarrow \) 1 muon pair per second envisaged.

C. Müller, Deneke & Keitel, PRL 101, 060402 (08); see also C. Müller, Phys. Lett. B 672, 56 (09)
Radiative reaction

\[ m_0 \frac{du^\mu}{ds} = -e F^{\mu\nu}_T u_\nu \]

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

\[ F^{\mu\nu}_T(x) = F^{\mu\nu}(x) + F^{\mu\nu}_S(x) \]

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

Damping & Reabsorption of initially emitted
Light alters Dynamics
• One first solves the inhomogeneous wave equation exactly with the Green's-function method

\[ \Box A^\nu_T = e \int ds \delta(x - x(x))u^\nu = j^\nu(x) \quad \Rightarrow \quad A^\nu_T(x) = A^\nu(x) + \int dx' D(x - x') j^\nu(x') \]

and then re-substitute the solution into the Lorentz equation:

\[ (m_0 + \delta m) \frac{d u^\mu}{d s} = e F^{\mu \nu} u_\nu + \frac{2}{3} \alpha \left( \frac{d^2 u^\mu}{d s^2} + \frac{d u^\nu}{d s} \frac{d u_\nu}{d s} u^\mu \right) \]

• After "renormalization" one obtains the Lorentz-Abraham-Dirac equation

\[ m \frac{d u^\mu}{d s} = e F^{\mu \nu} u_\nu + \frac{2}{3} \alpha \left( \frac{d^2 u^\mu}{d s^2} + \frac{d u^\nu}{d s} \frac{d u_\nu}{d s} u^\mu \right) \]

• The Lorentz-Abraham-Dirac equation is plagued by serious inconsistencies: runaway solutions, preacceleration

• 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)

\[ m \frac{d u^\mu}{d s} = e F^{\mu \nu} u_\nu + \frac{2}{3} \alpha \left[ \frac{e}{m} (\partial_\alpha F^{\mu \nu}) u^\alpha u_\nu - \frac{e^2}{m^2} F^{\mu \nu} F_{\alpha \nu} u^\alpha + \frac{e^2}{m^2} (F^{\alpha \nu} u_\nu)(F_{\alpha \lambda} u^\lambda) u^\mu \right] \]
• Radiation field emitted by an electron (Landau and Lifshitz 1947):

\[
E_{\text{rad}}(r, t) = -e \frac{n \times [(n - \beta) \times \dot{\beta}]}{(1 - n \cdot \beta)^3R}\bigg|_{\text{ret}}
\]

\[
B_{\text{rad}}(r, t) = n \times E_{\text{rad}}(r, t)
\]

• Main features of the radiation emitted by an ultra-relativistic electron:
  – radiation emitted at each instant mainly along the electron’s velocity within a cone with an aperture of the order of \(1/\gamma\)
  – radiation emitted at each instant with frequencies up to \(\omega_c = 3\gamma^3/\rho\), with \(\rho\) the curvature radius
• 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*10^{22} W/cm^{2}, focused to 2.5 μm (10 PW), pulse duration 30 fs.

Quantum radiation dominated regime

• At the same laser intensity, if one employs an electron beam with energy of 1 GeV, one can enter the so-called Quantum Radiation Dominated Regime (QRDR)

• In the QRDR the electron emits many photons incoherently already in one laser period and in each photon emission recoil is in principle significant

for semiclassical treatment see I. V. Sokolov et al., PRE 81, 036412 (2010)
Pulse shape effects: Radiation of laser driven electrons

Carrier envelope phase is measurable via spectra of an interacting electron, especially their boundaries

\[
\psi_A(\phi, \phi_0) = \sin^4\left(\frac{\phi}{4}\right) \sin(\phi + \phi_0) \quad \phi \in [0, 4\pi] 
\]  
(model of laser pulse)

Photon energy emission spectra in sr\(^{-1}\) for above pulse model and an electron bunch with central energy \(\varepsilon_{\text{mean}} = 26\) MeV spreaded by \(\Delta\varepsilon=2\%\) and transversal and horizontal beam waists \(w_x = w_y = 5\) \(\mu\)m and \(w_z = 8\) \(\mu\)m, respectively scattering from a focussed beam (Gaussian) with central frequency \(\omega=1\) eV and peak intensity parameter \(\xi = 100\) focussed to \(w_0 = 2\) \(\mu\)m (parts a,b)) with a CEP of \(\phi_0=-\pi/10\) (part a) and \(\phi_0=-\pi/5\) (part b)) (CLASSICAL REGIME) and a single electron with energy \(\varepsilon = 7.5\) MeV scattering from a plane wave pulse (parts c,d)) with central frequency \(\omega=50\) eV and an intensity parameter \(\xi = 20\) with a CEP of \(\phi_0=0\) (part c) and \(\phi_0=\pi/4\) (part d)) (QUANTUM REGIME)

Radiation reaction effects in plasma

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

In our setup a strong laser beam interacts with a plasma slab. We have investigated RR effects on the energy spectrum of the generated ion beam.

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

Laser and plasma parameters:
laser wavelength $\lambda=0.8$ μm,
laser intensity $I=2.33 \times 10^{23}$ W/cm$^2$, laser pulse duration 7 cycles, plasma density $n=100n_c$, plasma thickness $l\lambda$.


Negligible effects for circular polarization because the laser does not penetrate the plasma.

RR effects for linear polarization strongly narrow the ion spectrum.
MeV Acceleration and Nuclear Physics via Laser-Plasma Interaction


Dense monoenergetic proton beams from chirped laser-plasma interaction

- Introduce linear frequency chirp: \( f = f_0 + b_0 (t - z/c) \)
- Relativistic proton energies already at moderate laser intensities of \( 10^{21} \) W/cm\(^2\)
- Dense monoenergetic proton beams (1 % energy spread and \( 10^7 \) particles per bunch)
- Multi-GeV proton beams at future facilities like ELI, HiPER
- Analytical model agrees with 2D-PIC calculations

Figure: Snap-shots (a) of the electron and proton density distribution during laser-plasma interaction and (b) of the proton density distribution after laser-plasma interaction.

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>$^{153}\text{Sm}$</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>$^{181}\text{Ta}$</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>$^{225}\text{Ac}$</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>$^{223}\text{Ra}$</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>$^{227}\text{Th}$</td>
<td>$3/2^- \rightarrow 1/2^+$</td>
<td>37.9</td>
<td>...$^{(2)}$</td>
<td>18.68 d</td>
<td>...$^{(2)}$</td>
</tr>
<tr>
<td>$^{231}\text{Th}$</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 $^{223}\text{Ra}$ for laser parameters as in the DESY TESLA technical design report supplement

See also Adriana Palffy et al., Phys. Rev C (2007)
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),

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

Seeded XFEL

\[ \text{XFEL} \]

O

Seeded XFEL

\[ \text{XFEL} \]

O

(see also Liao et al, PRL in press and arXiv 2012 on x-ray photon storage)
Nuclear tunneling and recollisions in laser-assisted α decay

Non-relativistic process
Semi-classical parameter regime
Tunneling rate is barely influenced by a strong optical laser (800 nm).

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

Conclusions

**Laser-vacuum interaction:** Vacuum refractivity, matterless double slit, pair creation,

**Laser-electron interaction:** GeV laser colliders, pair creation, radiative reaction, cascades

**Laser-ion & nuclei interaction:** ion acceleration for cancer treatment, nuclear population transfer, laborat. astrophysics