Introduction

The continuous development of novel laser sources with ever increasing intensities and frequencies has established the meanwhile mature scientific area of extreme-field laser science. The so-called “Extreme Light Infrastructure” currently under construction in Prag, Bucharest and Szeged constitutes one of Europe’s largest and most expensive research facilities in this area and will deliver light sources sufficient to carry out competitive nuclear and high-energy physics with laser fields. The use of free-electron lasers will strongly enrich the field of nuclear physics and in combination with traditional accelerators the vacuum can be rendered instable and quantum electrodynamics as well as weak interactions may be tested in unexplored regimes. The precise control of lasers is also likely to allow for applications including laser-based laboratory astrophysics, laser colliders and laser-triggered nuclear batteries. In this section, we begin with an introduction into the dynamics of free as well as “ion and vacuum bound” electrons in strong laser pulses and focus on the intrinsic quantum features of relevance in such situations. The radiation in ultra-strong laser pulses and their back action on the dynamics in the quantum regime of hard photons will be the key topic of the second part. Then, we address the important question how the spatial extent of vacuum fluctuations can be enhanced with the aim to establish a laser-based collider and how weak interactions could be tested with extreme photon background fields. In the two final contributions the role and the technical handling of ultra-short pulse shapes and the virtues of laser-based nuclear excitations are investigated.

Relativistic Quantum Dynamics in Extremely Intense Laser Pulses: Spin Effects, Pair Creation and Tunneling Times

The fundamental interaction of light and matter is governed by the laws of quantum mechanics. This is even of relevance for electrons and positrons in ultra-strong laser pulses being composed of a very large number of photons. Furthermore, quantum mechanics often challenges our intuition when confronting us with phenomena that are beyond our daily experience, for example, wave-particle duality, nonlocality, spin effects, tunneling or pair creation. For this reason, (semi) classical models are commonly applied to describe phenomena of the quantum world. Such models are valuable for obtaining an intuitive understanding of quantum effects. Furthermore, models of (semi) classical physics are mathematically and computationally often much more easy to solve. In particular, many-particle quantum systems cannot be simulated efficiently on a classical computer and are often also hard to treat analytically.

According to classical electrodynamics the motion of an electron is determined by the Lorentz force. This force is induced via an interaction of the electron’s charge with the electromagnetic fields. The Lorentz force (in its standard form) does not account for the electron’s spin degree of freedom, which naturally emerges within the framework of relativistic quantum mechanics and the Dirac equation. Therefore, different classical theories have been put forward and are commonly applied in various branches of physics to describe the relativistic dynamics of electrons by coupled equations for the orbital motion and spin precession. Little, however, is known how well these classical models agree with the more fun-
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One of the most intriguing predictions of quantum electrodynamics is certainly the tunneling picture of pair creation, however, becomes inapplicable in the presence of magnetic fields (in addition to the electric field). For this reason, the tunneling picture was generalised to this situation in order to account also for magnetic fields in (2) (see Fig. 2). The new tunneling picture comprises the electron's (positron's) kinetic energy (dashed line in Fig. 2) and a pseudo energy (solid lines in Fig. 2), which depends on the magnetic field and is possible external photon. Various features of pair creation can be inferred qualitatively from the enhanced picture. For example, an additional photon lowers the potential barrier due to the photon's energy but also increases the particle's relativistic mass due to the photon's additional momentum. Due to this increased relativistic mass, the electron and the positron stay ’longer’ under the barrier until they gain enough energy to become real. An additional magnetic field, however, will also change the momentum under the barrier and, in this way, the relativistic mass. Depending on the magnetic field’s direction and magnitude it may counteract the increase of the relativistic mass. Depending on the magnetic field's direction and magnitude, the electron and the positron may stay under the barrier for a longer time before radiating a photon, it can find itself in the strong fields in the centre of the pulse with an energy larger than that of its companions. As a result, it is much more likely to emit an energetic photon. In contrast, the classical picture predicts the same emissivity for all particles with the same initial conditions, since these uniquely define the trajectory. Quantum effects can, therefore, be detected by measuring either the electron distribution after propagation through the laser pulse, or the spectrum and angular distribution of the gamma-ray photons emitted inside the pulse. In (4) we have used a Monte-Carlo simulation technique to quantify these effects as they appear in the configuration shown in Fig. 3, allowing for the finite transverse extent of the pulse as well as its finite duration. As expected, we find that the electron distribution that emerges from the pulse has a much larger spread in energy than it would be expected in the classical case. However, the relatively large number of electrons that fail to pass through the regions with the strongest field significantly dilutes this signal. Consequently, we find that the most sensitive indicator of quantum effects is the yield of very high energy photons: when electrons of 1 GeV pass through a laser pulse of peak intensity $10^{22}$ W cm$^{-2}$ in the experimental configuration of Fig. 3, the number of photons emitted with energy greater than 600 MeV exceeds the classical prediction by more than one order of magnitude.

Generally, the detection of various modifications of the radiation spectrum due to quantum radiation reaction requires accurate quantitative measurements. However, in (5) we have identified signatures of quantum radiation reaction for Compton radiation spectra which are easily detectable in an experiment due to distinct qualitative characteristics. We have investigated features of the angle-resolved spectrum of Compton radiation when an ultra-relativistic electron beam counterpropagates with a strong focused ultrashort laser pulse of variable duration. With increasing laser-pulse duration the angular spread of radiation is shown to initially rise in a narrow range due to laser focusing and then continuously decrease because of quantum radiation reaction. This unique behaviour does not occur for previous experiments performed with lower laser intensities. In contrast, the quantum radiation reaction exhibits a strong dependence on the angle of incidence of the laser pulse. When the laser pulse is incident at an angle of 45 degrees, the angular spread of radiation is significantly reduced compared to the case of laser incidence at normal incidence. In addition, the quantum radiation reaction leads to a significant enhancement of the Compton yield, which increases with increasing laser intensity. This effect is not observed in classical radiation reaction, where the Compton yield is independent of the laser intensity. Furthermore, the quantum radiation reaction also affects the energy distribution of the emitted gamma-rays. In classical radiation reaction, the energy distribution of the gamma-rays is purely determined by the electron energy and the Lorentz factor of the electron. In contrast, the quantum radiation reaction leads to a non-monotonic energy distribution of the gamma-rays, which depends on the laser intensity and the angle of incidence of the laser pulse. This non-monotonic energy distribution is a direct consequence of the quantum radiation reaction and cannot be observed in classical radiation reaction.
not exist in the classical radiation reaction regime. The spectral bandwidth of the radiation in the quantum regime is by orders of magnitude larger than in the classical regime. The qualitative behaviors mentioned are robust and observable in a broad range of electron and laser-beam parameters.

The quantum radiation reaction can also be harnessed for the generation of ultrashort gamma-ray pulses, which are aspired for time resolved nuclear spectroscopy. In [6], we demonstrated the feasibility of multi-MeV gamma rays of several hundreds of attoseconds duration via nonlinear Compton scattering of an intense laser pulse by a counterpropagating electron beam of much longer duration. We found an interaction regime where only a small fraction of the electron beam loses sufficient energy due to radiation reaction to be reflected and emits gamma rays close to the laser propagation direction during a short time while leaving the laser focal region, see Fig. 4. The length of the gamma-ray pulse is much shorter because the front of the gamma pulse and the tail of the electron beam counterpropagate.

The scheme relies on the nonlinear effects of the regime of interaction, the tightly focused driving laser pulse, and these ingredients are necessary to realise the ultrashort duration of the emitted gamma rays determined solely by the intrinsic interaction mechanism and yielding brilliant attosecond gamma-ray bursts.

High-Energy Processes in Ultra-Intense Laser Fields

The Heisenberg uncertainty principle represents one of the most profound conceptual novelties in quantum mechanics. In the realm of quantum field theory it implies the existence of "vacuum fluctuations" of virtual particles-antiparticles. As electrons and positrons have a finite mass, the conversion of a photon into a real electron-positron pair violates energy-momentum conservation and is forbidden in vacuum. According to the Heisenberg uncertainty principle, however, this transformation is "temporarily" allowed and virtual pair can cover a distance comparable with the order of the Compton wavelength $\lambda_C \approx 3.9 \times 10^{-11} \text{cm}$ (see Fig. 5a). As to be anticipated, the presence of vacuum fluctuations leads to qualitatively altered theoretical predictions. Among them, the most appealing examples are the feasibility of light-by-light scattering. Classically, the superposition principle does not allow waves to overlap and emit vacuum fluctuations. This becomes possible in the quantum regime, which is by orders of magnitude larger than the age of the universe, which renders the experimental investigation of this process extremely challenging. The presence of strong electromagnetic background fields, however, catalyses the radiative decay and enhances the photon-neutrino coupling by several orders of magnitude (see Fig. 6a). In the light of this observation, we have investigated the interactions between photons and neutrinos in a vacuum and have shown that neutrinos play an active role in the present understanding of virtual particles. Among them, since the discovery of the Higgs boson, neutrinos represent the last of the fundamental constituents of the Standard Model. Moreover, as optical photons as well as neutrinos are being tested in the regime of quantum field theory in the presence of strong electromagnetic background fields, the study of neutrinos in the context of quantum field theory in the presence of strong electromagnetic background fields becomes particularly interesting.


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Ultrarelativistic Electron States in a Tightly Focused Laser Beam

Due to their ever increasing power, strong optical laser fields are becoming a unique tool to test quantum electrodynamics (QED) in yet unexplored regimes where quantum nonlinear effects dominate the particles' dynamics. The electric field strength where such nonlinear effects become sizable identifies the 'strong-field QED' regime and is given by the so-called Schwinger field or critical field of QED, \( E_{c} = 1.3 \times 10^{18} \text{ V/cm} \). Due to the extremely large value of \( E_{c} \), present and upcoming lasers have to be tightly focused in space and in time in order to approach \( E_{c} \). Nonetheless, the value of \( E_{c} \) exceeds by about four orders of magnitude presently available laser-field amplitudes. However, the effective field at which a QED process occurs is that experienced by participating charged particles in their rest frame. Thus, by employing, for example, ultrarelativistic electron beams, the strong-field QED regime can be in principle already effectively probed. In fact, electron beams with energies of about 5 GeV (approximately corresponding to a relativistic Lorentz factor of 10^4) are already available also by employing modern laser-wake-field acceleration techniques. Nonlinear approximations that in order to enter the strong-field QED regime at present and upcoming laser facilities, the electrons have to be so highly relativistic that the Wentzel-Kramers-Brillouin (WKB) approximation can be employed (at the next-to-the-leading order) to solve analytically the Dirac equation in the presence of a background laser field practically of arbitrary space-time shape. The physical reason is that, by requiring that the electric field of an optical laser (laser photon energy of the order of 1 eV) in the rest frame of an electron beam is of the order of the \( E_{c} \), automatically implies that the Lorentz factor of the electron bunch is so large that the electrons are barely deflected by the laser field itself. The electron wave functions obtained in this way open the possibility of investigating analytically and in a systematic way strong-field QED processes in the presence of a tightly focused laser beam of complex and realistic space-time shape by employing the so-called Furry picture. Indeed, we have already determined analytically the energy spectrum and the angular distribution of the electron-positron pairs produced in the collision of a photon bunch with an intense and tightly-focused laser beam (nonlinear Brem-Wheeler pair production) [9]. As a Born product, by means of a numerical implementation of the analytical results, we have proven that the inclusion of the laser tight focusing is essential for a correct quantitative estimate of the number of created pairs. In fact, we have expected, approximating a tightly focused laser field as a plane wave would largely overestimate the number of produced pairs especially in those regions close to but not exactly at the laser peak (see Fig. 7).

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Nuclear Processes in Ultra-Intense Laser Fields

Recent experimental developments in laser physics promise to open the new field of laser-induced nuclear reactions in a so far unexplored domain. Efforts are under way to generate a multi-MeV laser beam at the Nuclear Physics Pillar of the Extreme Light Infrastructure (ELI) and at the International Center on Zetta-Exawatt Science and Technology (IZEST). The prospect of a laser beam with photon energies comparable to typical nuclear excitation energies raises important questions. How will an intense laser pulse interact with a medium-weight or heavy nucleus? To answer this question, we first have to consider that the nucleus is bound by the strong force. As a consequence, the laser-nucleus interaction is much weaker than its more studied counterpart, the laser-atom interaction. Furthermore, processes which differ significantly from the standard photon-induced nuclear reactions are expected to occur only if the gamma-ray photons in the laser pulse are coherent. It is only via coherence that the dipole absorption rate may attain values in the MeV range, rendering it comparable to other characteristic nuclear energy scales.

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References