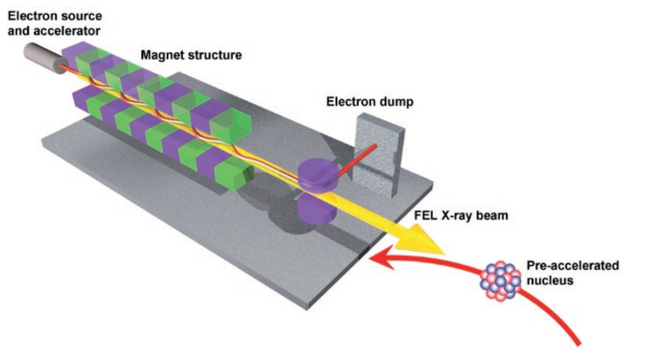
The muon is a particle similar to the electron, but having an about 200-fold higher mass. Thus, for a muonic atom in a laser field, the drift by the light pressure is strongly suppressed. Additionally, the muon is circulating at a much shorter distance from the nucleus compared to the light-weight electron. So it may be used as a probe for properties of the atomic nucleus. First model calculations demonstrate that the different nuclear radius of hydrogen compared to deuterium (“heavy hydrogen”) leads to a different yield of higher harmonics of the laser frequency. Hence, the observation of this radiation could provide insight into nuclear properties.

On the Way to Nuclear Quantum Optics

Future sources of super-intense X-ray laser beams like the free-electron laser XFEL at DESY will enable a direct interaction of the X-ray light with pre-accelerated atomic nuclei. Initial theoretical studies of this interaction show that it will be possible to determine the properties (shell structure, charge distribution) of a nucleus by optical means due to such a resonant excitation of the nucleus. Quantum optics which meanwhile represents an exceedingly successful method in atomic physics for preparation, control, and detection, may thus be transferred to nuclear physics. This will make the new field of nuclear quantum optics accessible. Recent calculations demonstrate, that multiphoton-muon pair creation in collisions of relativistic naked heavy ions with X-ray laser beams also offers access to nuclear properties.



Schematic drawing of a free-electron laser (left, image: DESY). The X-ray laser beam (yellow) collides with an accelerated atomic nucleus (right).

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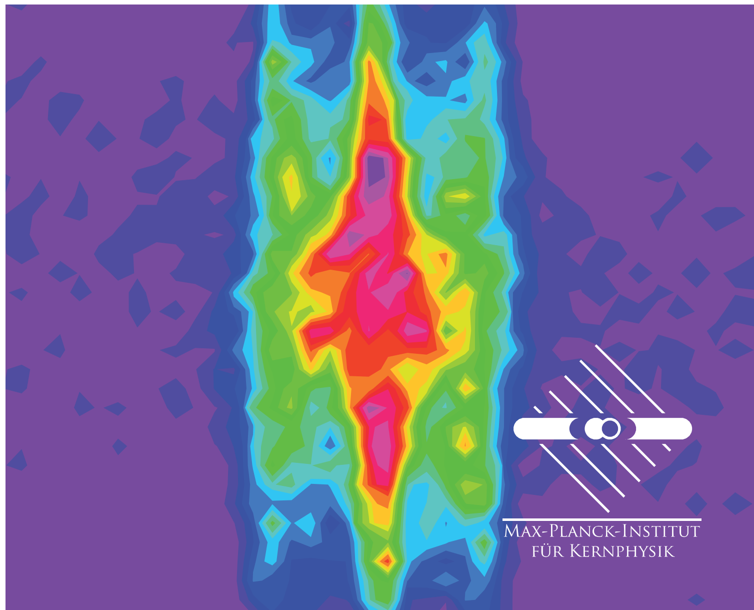
Laser-Modified Quantum Electrodynamics, Nuclear and High-Energy Processes

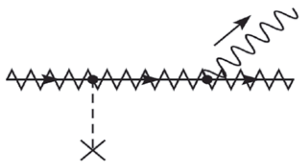


Laser-Modified Quantum Electrodynamics, Nuclear and High-Energy Processes

The structure of the vacuum is described in the framework of quantum electrodynamics. Quantum-electrodynamical effects under the influence of a very intense laser field lead to the coupling of photons to vacuum fluctuations. Collision processes of charged particles in strong laser fields can be used to produce new particles and to investigate and to control properties of atomic nuclei. The direct interaction of intense laser beams in the X-ray region with atomic nuclei opens up the new field of nuclear quantum optics.

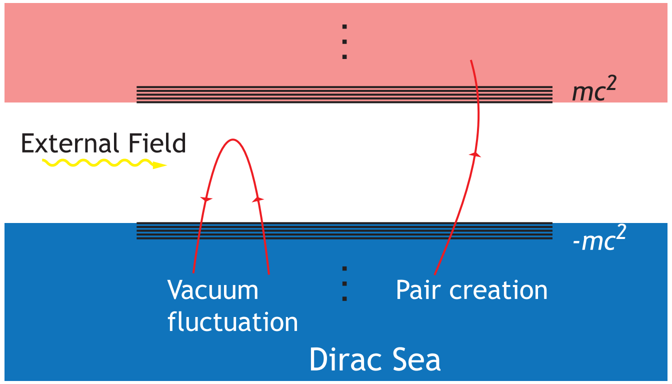
Quantum Electrodynamics in Intense Fields

Using quantum electrodynamics, it is possible to calculate the inner structure of matter (e.g., of highly charged ions) with high precision. The results are scrutinized with precision experiments in ion traps at the MPIK and in the storage rings of the MPIK and the GSI. This provides new methods for the measurement of nuclear properties. The energy stored in a metastable atomic nucleus of a highly charged ion can be released on electron capture like from an extremely energetic battery. Highly precise calculations of bound states are the basis for a determination of natural constants with a relative accuracy of 10^{-14}. The strong electromagnetic fields within the systems under consideration are playing a crucial role for these calculations.



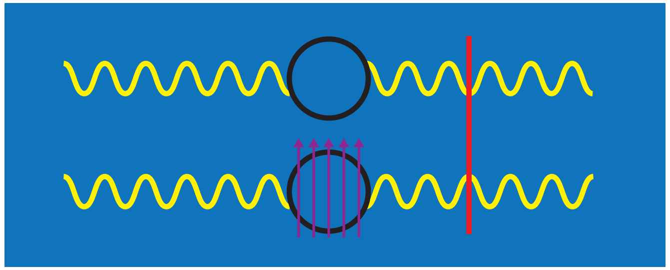
Feynman graphs for laser-assisted Bremsstrahlung. The zig-zag line represents an electron embedded in the laser field, the broken line the interaction with the nucleus and die wavy line the emitted X-ray quantum.

The superposition of very strong external fields with intense laser beams is of equally high interest. Such a combination modifies the structure of the vacuum. By means of quantum electrodynamics, it can be investigated how this influences certain processes. If an electron is scattered at an atomic nucleus, it can release its energy in the form of X-rays ("Bremsstrahlung"). Embedded in a very strong laser field, the electron gains new properties that demand for an exact calculation of the coupling to the field.



The Dirac sea describes the vacuum as an infinite sea of particles possessing negative energy, with all states occupied. In contrast, all states of positive energy are empty. Under the influence of an external field, a virtual particle-antiparticle pair (vacuum fluctuation) can be transformed into a real paticle pair.

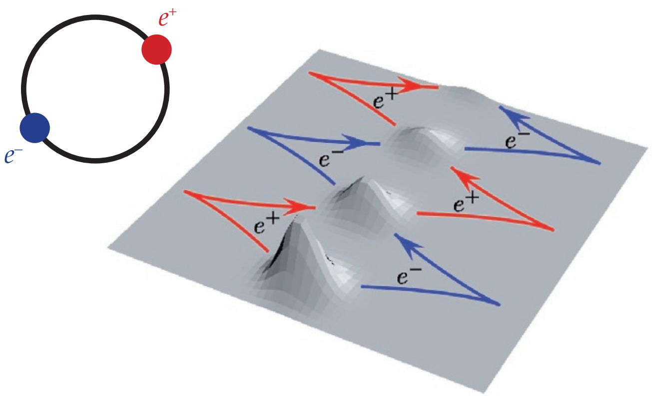
In another study, the merging of a large number of laser photons to a few extremely energetic photons during the collision of highly energetic protons with an intense laser beam has been investigated by complete calculations taking into account the polarization of the vacuum (shift of virtual charged particles against each other). The latter also induces a change of the optical refractive index of the vacuum, which for example leads to originally linearly polarized light becoming elliptically polarized and rotated. A quantitative estimation shows that measuring such vacuum effects is experimentally feasible.



The optical refractive index of the vacuum is changed in the presence of a strong standing wave (bottom); this induces a phase shift of the probe X-ray laser beam.

Atomic Colliders

An electron, released from an atom in an intense laser field, is first driven back and forth by the laser field and may recollide with its parent ion. This recollision can induce multiple ionization of the atom and produce higher harmonics of the laser frequency. At very high laser intensities, the electron reaches even relativistic velocities. However, in this case, the electron is driven away from the atom by the "light pressure", preventing the recollision. For certain "exotic" atoms, this effect can be circumvented. Positronium consists of an electron and a positron, its (positively charged) antiparticle. Because of the identical drift motion, repeated highly energetic recollisions take place: The system represents a miniature collider, which allows the generation of new particles from the collisional energy. The illustration on the front page of this folder shows the calculated density distribution of the particles in the instant of recollision. Pair production of muons has been predicted theoretically for this recollision process.



Positronium in a very intense laser field. Due to their identical masses, electron and positron experience the same drift motion in propagation direction, such that repeated recollision of the wave packets can occur.