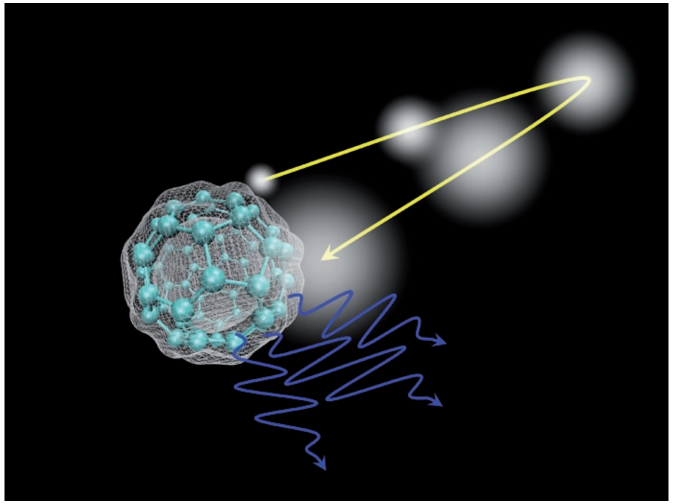
Collective Effects

In larger ensembles of nearby atoms exposed to strong laser fields, collective effects play a role, e.g., when during the recollision with a C_{60} fullerene its electron shell is excited as a whole to perform vibrations. This in turn influences the radiation emitted which contains useful information about the inner structure of such a complex object.



In an intense infrared laser pulse, a part of the electron shell of a C_{60} fullerene is detached and driven back and forth by the laser field as a "wave packet" (represented by the light-grey cloud). During the recollision with the fullerene both its remaining electrons are excited to perform vibrations and high harmonics of the laser light are emitted in the form of short-waved light pulses (blue lines).

Collective effects may lead to the intensity of fluorescence light becoming proportional to the square of the number (instead of directly to the number) of atoms or to metal clusters absorbing infrared laser light very efficiently. Clusters consisting of, e.g., 1000 to 100 000 argon atoms are converted by intense lasers into a so-called nanoplasma within a few femtoseconds, i.e., electrons are separated from the atoms. Harmonics of the laser frequency are resonantly amplified therein if their frequency meets the eigenfrequency of the nanoplasma. Laborious "particle-in-cell" simulations model the complex expansion dynamics and the conversion of laser energy into particle energy.

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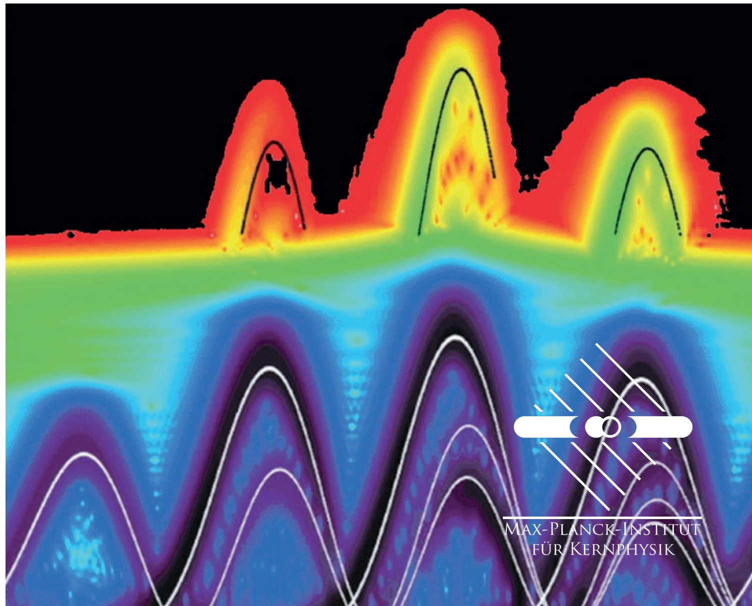
Theory of Collective and Relativistic Quantum Dynamics in Strong Laser Fields



Theory of Collective and Relativistic Quantum Dynamics in Strong Laser Fields

When intense laser fields interact with matter, the behavior of the electrons plays a prominent role, because these, being light charged particles, strongly couple to the outer field and thus efficiently absorb energy from the field. Thereby they can become so fast that the effects of the theory of special relativity play an important role. This requires the search for solutions of the time-dependent Schrödinger and Dirac equations, the basic equations of non-relativistic and relativistic quantum mechanics, respectively.

Recollision

The simplest case of the classical motion of a charged particle in a linearly polarized laser field for the example of the field ionization of a helium atom is illustrated in the figure below: The two electrons are initially bound within the electrostatic Coulomb potential which here appears as a "funnel" in the plane potential surface of the representation reduced to two spatial dimensions. The electrical field of the laser (indicated by the yellow sinus curve) induced an inclination of the plane that oscillates with the laser frequency. An electron detached from the atom by field ionization shortly after the maximum of the field is first driven away from the atom by the laser field, but then back again and may, e.g., set free further electrons from the atom. A descriptive measure for the energy of the electron in the laser field is given by the so-called "ponderomotive energy" U_p that corresponds to the time-averaged quiver energy of the oscillating particle. The maximum energy attainable in the recollision amounts to $3.17\,U_p$. In case of very high laser intensities, the electron reaches even relativistic velocities, but is driven away from the atom by the interaction with the magnetic component of the laser field, the "light pressure"; thus the recollision is prevented. The theory permits modeling of diverse procedures that circumvent this effect. Thus collisions at much higher energies can be obtained, so that, e.g., new particles may be generated.

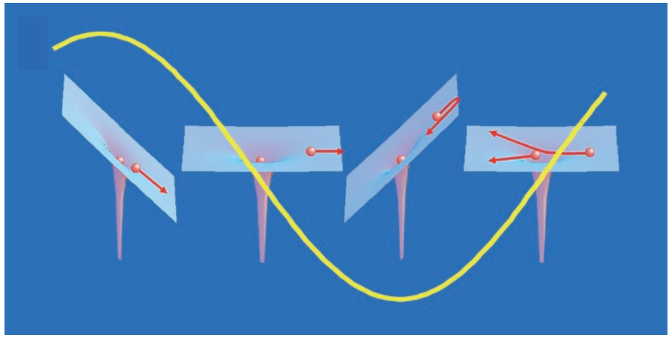


Illustration of the recollision of an electron in a linearly polarized laser field. Shown is the potential in two dimensions as a plane periodically inclined by the electrical field of the laser with the funnel-shaped Coulomb part of the nuclear field. An electron detached by field ionization is driven back and forth by the laser field and set free another electron when recolliding with the parent ion.

Higher Harmonics and Double Recombination

In the recollision, an electron may release its energy in the form of short-waved radiation when it is decelerated or, in the extreme case, recombines with the parent ion. Since the oscillation of the driving field is superimposed on the electron's motion, the radiation is emitted in the form of higher harmonics of the laser frequency. Higher harmonics are being widely applied, for example for the generation of coherent UV radiation with ultra-short pulse lengths down to the regime of attoseconds. The maximum energy of the radiation is given for a single electron by the sum of the translational energy and the binding energy (ionization potential I_p): $E_{max} = I_p + 3{,}17\,U_p$. When two electrons are released one after the other by field ionization and then caught simultaneously by the ion, higher harmonics up to $2 \cdot 3{,}17\,U_p + I_p(1) + I_p(2)$ may be produced, whereby $I_p(1)$ and $I_p(2)$ correspond to the two ionization stages. The illustration on the title page shows the spectrum of the radiation emitted, covering two laser cycles in the center of a laser pulse of 800 nm wavelength, which has been calculated by an ab-initio procedure. It shows the radiation expected, stemming from the recombination of a single electron as well as – even though considerably weaker (the color scale of the intensity is logarithmic) – the more energetic radiation resulting from the two-electron recombination. The results agree remarkably well with the simple classical model (black and white lines).

Strong Acceleration by Intense Laser Pulses

According to theoretical calculations performed recently, linearly or radially polarized, tightly focused and thus extremely strong laser beams should permit the direct acceleration of light atomic nuclei over micrometer-sized distances up to energies that may offer the potentiality for medical applications.

Quantum Interferences

The optical properties of an ensemble of atoms can be strongly altered by exposing the atoms to moderately intense laser fields which induce quantum-interference effects by resonant couplings. Among them are electromagnetically induced transparency, lasing without the occupation inversion of the involved quantum states normally required, or control of the refractive index. In a dense gas of metastable neon atoms, it is theoretically possible to induce a negative refractive index by suitable pumping laser fields. Conditions are predicted under which the probe infrared laser beam is not absorbed but on the contrary amplified.

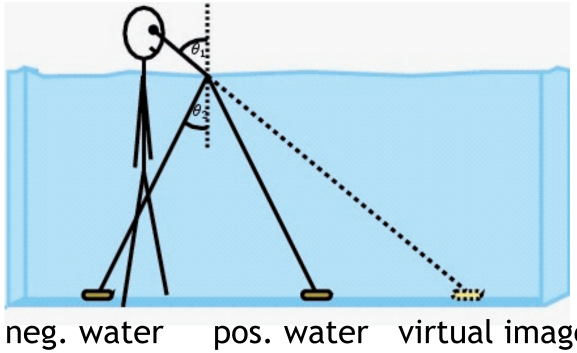


Illustration of the negative refraction compared to the normal positive refraction. The observer "sees" the virtual image.

In optical lithography, interferences also make it possible to produce structures that are much smaller than the laser wavelength. As shown by the calculations, phase-shifted standing waves induce in the photoresist a pattern with high contrast by means of resonant interactions between atoms and laser field. This mechanism does not require multiphoton processes which are hard to realize and works at low laser intensities.