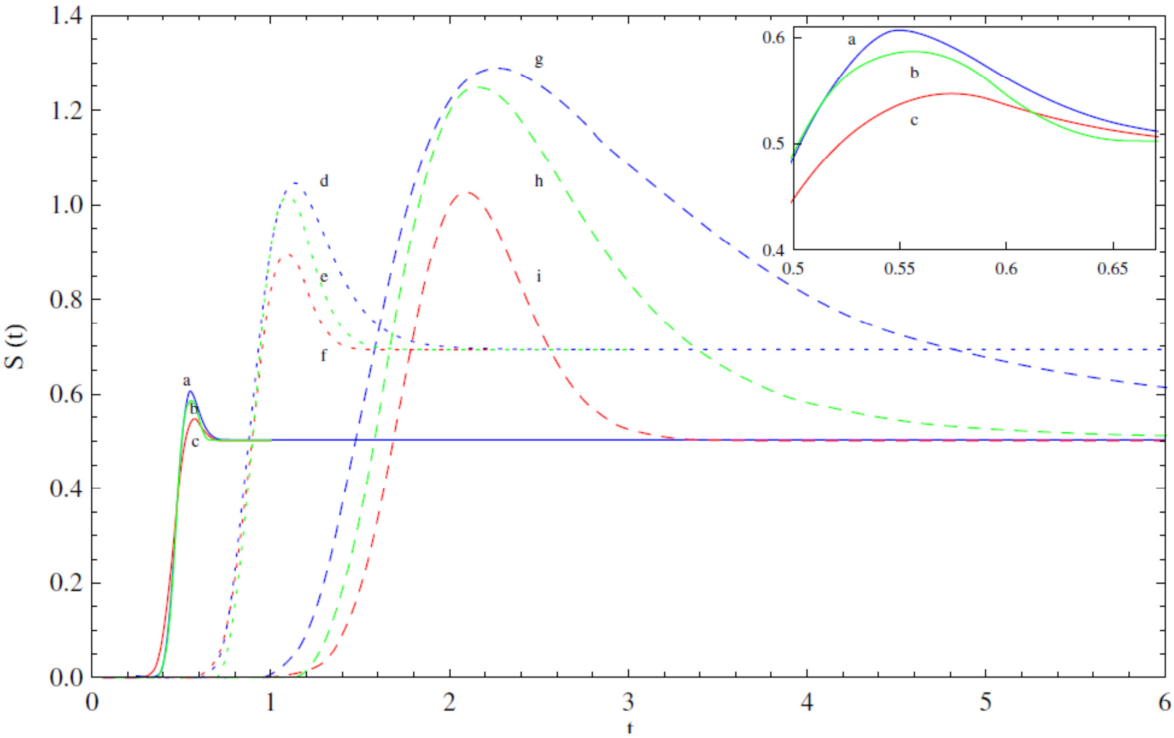
FINAL REPORT ON THE RESULTS OF THE PROJECT OTKA K81364

Emission and control of electrons from atomic and solid state systems by electromagnetic pulses

Time dependence of colllision generated position entanglement of particles

The state of a subsystem of a quantum mechanical system can be described only by a (reduced) density operator, even if the whole system is in a pure state. There can be a strong quantum correlation between the subsystems (parties) of the total system, that has no classical counterpart. This is called quantum entanglement, and it has fundamental importance in quantum measurements and in quantum informatics.

In our work [8] first we have considered the time evolution of coordinate space entanglement between a pair of colliding particles in a one-dimensional scattering situation. If the potential is approximated by a Dirac delta function, then the propagator of the relative motion can be given in a closed form, but still the corresponding wave function cannot be obtained in an explicit analytic form, even if the initial state is a well behaving Gaussian function. We succeeded to give an asymptotic expression for the propagator, and the appropriate analytic wave function could be obtained for time instants long after the collision. This splits the relative wave function into two distinct Gaussians: one that corresponds to the forward scattered wave, while the other yields the reflected wave. The great advantage of this approximate form is that it allowed us to proceed entirely analytically and determine the total wave function as well as the final value of the entanglement in the system in a closed form. For the quantification of the quantum entanglement, we use the von Neumann entropy, since this can be calculated in a straightforward way from the eigenvalues of the reduced density operators. We also followed the time evolution of the entaglement during the process of collision, in this case we calculated the entaglement entropy by numerical methods. The following figure gives an overview about the time dependence of quantum entanglement for different initial momenta and mass ratios.



Time dependence of the quantum entanglement during the collision process. The two particles are start to move towards each other at t=0 with relative momentum q. We plot the Neumann entropy, computed numerically, versus time (in appropriate units) in nine cases. Here tc is the instant of the corresponding classical collision, and g is proportional to the strength of the delta potential. For solid curves (a)–(c) q/|g| = 2, tc = 0.5; for dotted curves (d)–(f) q/|g| = 1, tc = 1; for dashed curves (g)–(i) q/|g| = 1/2, tc = 2. For curves (a), (d) and (g) (blue), m1 = m2 = 1; for curves (b), (e) and (h) (green), m1 = 1, m2 = 2; for curves (c), (f) and (i) (red), m1 = 1, m2 = 10. The inset shows curves (a)–(c) zoomed into the peak region..

Oscillations in quantum entanglement during rescattering of an atomic electron due to a strong laser pulse

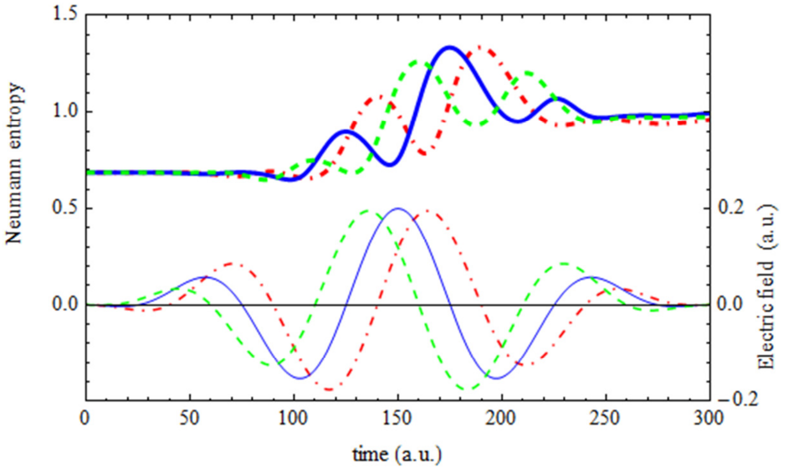
The entanglement appearing in the collision of two particles has growing relevance in the context of attosecond physics, since it is natural that measurements performed on the interacting particles, electrons and ions or ionized molecules, bear witness to the quantum features of the process. We have studied [10] the quantum entanglement in a fundamental process of attosecond science: during the rescattering of an electron, driven by a strong few-cycle laser pulse, on its parent ion–core. This is the underlying process for creating single attosecond pulses via high harmonic generation in a noble gas.

We use dipole approximation for the interaction of a single active electron and its parent ion with the classical electromagnetic field in the length gauge. We approximate the interaction between the active electron and the ion–core by a Dirac delta potential. We consider a linearly polarized laser pulse and we keep the treatment in one spatial dimension.

The time evolution of the centre of mass wave function is simple spreading, but the solution for the relative motion needs numerical simulation. We use a higher-order (Numerov extended) Crank–Nicolson scheme. We set the strength of the delta potential such that its single bound state has the same energy as the ground state of the hydrogen atom. We approximate the electric field of a three-cycle cosine laser pulse by a sine-squared envelope, multiplied with a carrier of a period of 100 au (see the lower part of the figure below), which means low frequency compared to the ionization potential. This pulse excites the atom from the following initial state: the relative wave function is the single bound state of the Dirac delta potential, while the center of mass wave function is a Gaussian with its width fitted to the size of a hydrogen atom.

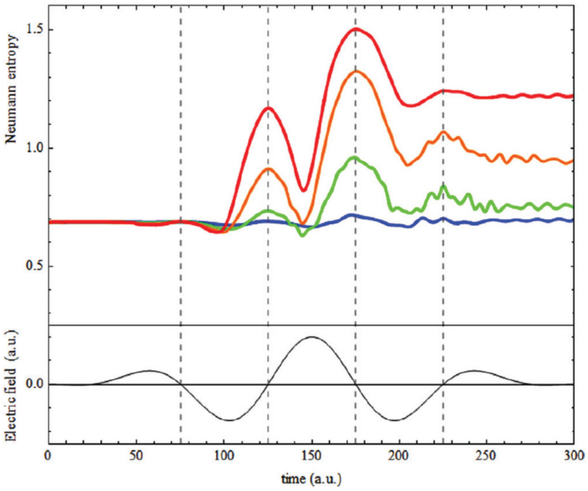
The quantum state of the system is the product of the relative coordinate wave function with the wave function of the center of mass motion, for all time. However, this quantum state is generally not a product state in the electron and ion–core coordinates: there is quantum entanglement between the electron and the ion–core. We computed the Neumann entropy of this quantum entanglement with numerical methods from the solution of the time dependent Schrödinger equation.

As shown by the figure below, the local maxima of the oscillations in the Neumann entropy coincide with the zero crossings of the electric field of the laser pulse, regardless of the carrier-envelope-phase (CEP) of the laser pulse.



These results indicate, that it seems possible to control the quantum entanglement between electrons and ions with the help of the laser pulse.

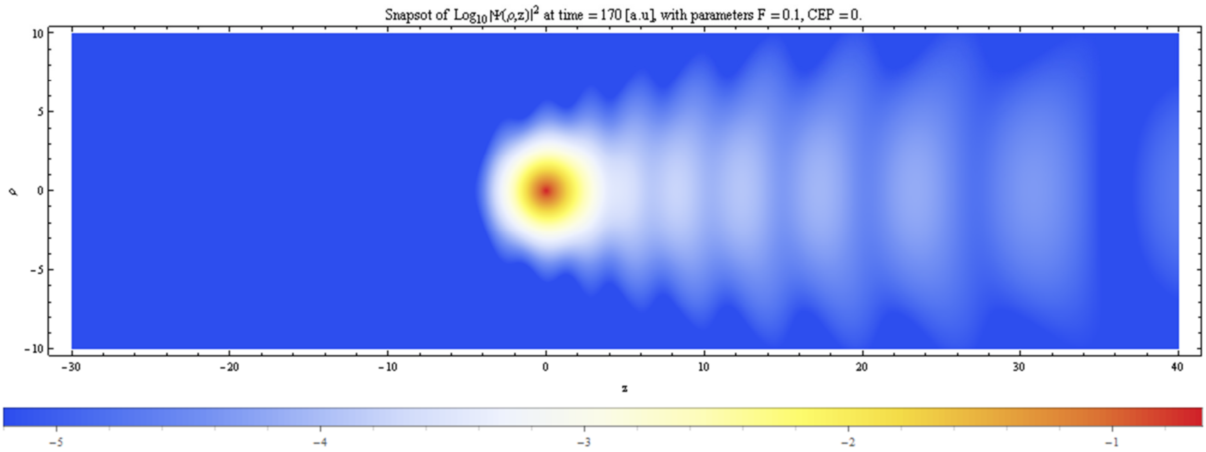
The next figure shows how the oscillations in the quantum entanglement emerge, as the laser intensity is increased.



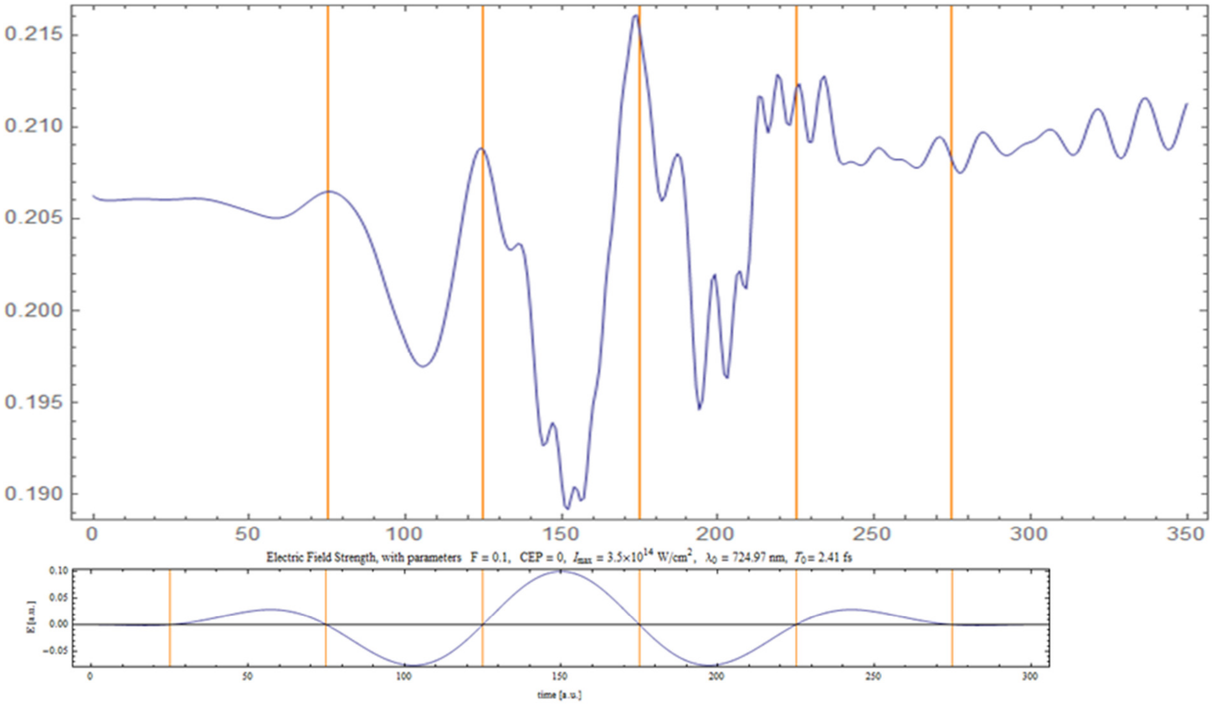
Neumann entropy versus time (in atomic units), for increasing peak values of the electric field. Black curve in the lower part: electric field −E(t) (= eE(t), i.e. the electric force acting on the electron, in atomic units) of a three-cycle pulse with a sine-squared envelope. Colour curves in the upper part: Neumann entropy SN(t), for peak electric field 0.1 au (blue), 0.15 au (green), 0.2 au (orange), 0.25 au (red).

These results inspired us to extend our investigations and simulations to 3 spatial dimensions [17] where one-electron atoms with Coulomb potential between the single active electron and the ion-core can be studied. In order to reduce computational costs, we consider linearly polarized laser pulses (which are applied in practice e.g. to generate single attosecond pulses), since then the cylindrical symmetry of the system enables to reduce the numerical problem to 2 spatial coordinates. We developed a new numerical method to solve the time-dependent Schrödinger equation for such a system very accurately and effectively. A paper is in preparation about the method, to be submitted to Computer Physics Communications.

The following figure illustrates the escape of the electron from the ground state of a H-atom due a strong laser pulse (optical tunneling), with electric field pointing in the –z direction, based on the simulation results with the new method and code.



The following figure shows a novel measure of quantum entanglement between the rescattering electron and the ion-core, as the function of time. The interesting feature of the coincidence of zeros of the electric field with the local maxima of the entanglement is clearly seen also in this 3D case.



In a more recent approach we have begun to investigate the CEP-dependence in the photoionization of a hydrogen-like atom in intense, pulsed laser field [16]. According to our calculations, the total ionization yield observably depends on the carrier-envelope phase of the exciting laser pulse, as well as on the initial state of the atom. The CEP dependence is more pronounced for superpositions like 1s-2p, where the initial dipole moment is not zero. These results can be useful for the design of pump-probe experiments, where the pump pulse is e.g., a “conventional” π/2 pulse, while the probe is a phase stabilized femtosecond pulse. These calculations are to be continued in the future.

Proposals to achieve efficient production of attosecond pulses with high-harmonic generation

High-order harmonic generation (HHG) in a noble gas medium is currently the widely used method to produce coherent radiation in the XUV and soft-x-ray regime. The elementary laser-atom interaction leading to HHG is understood via the three-step model, but the complete description of the HHG process requires considering the elementary laser-atom interaction together with the macroscopic aspects of laser and harmonic field propagation in the ionized gaseous medium. The temporal, spectral, and spatial distortions of the fundamental pulse during propagation result in a varying intensity and phase which strongly influence the produced harmonic radiation on both the single-atom and the macroscopic level The ultimate goal in an experiment is to obtain intense, coherent XUV or soft-x-ray radiation which in turn are useful in the designed applications like molecular imaging or pump probe experiments.

In order to obtain good quality harmonics, which is the result of the interference of individual atomic emissions, the phase differences between the waves produced by the atoms at different positions in the sample must be kept constant to achieve constructive interference. According to our proposal given in [9] this quasi-phase matching (QPM) condition can be achieved by using an extra THz field, which imposes the required time evolution of the atomic process. The advantages of this new scheme are multiple: strong THz pulses can be generated by optical rectification of femtosecond laser pulses, and as such the resulted THz pulse is inherently synchronized in time with the laser pulse generating the harmonics; fine control in space and time is available by tuning the wavelength, peak amplitude, chirp rate, and initial phase, thus the shape of the THz pulse can be adapted in order to optimize QPM and harmonic yield.

We have also considered [15] another possibility to achieve good quality attosecond pulses, namely the application of tailored excitation. To this end a genetic algorithm has been applied in a model situation to optimize gas high-order harmonic generation with a multivariable light-field synthesizer device. We inserted only the single-atom response, with limited temporal integration, in the optimization cycle due to processor time limitations, but afterwards each selected driver waveform was checked with a 3D macroscopic model. We found that whereas an unoptimized light-field synthesizer delivers 73-as pulses, the genetic optimization delivers driver wave forms that produce 55-as pulses that remain robust after propagation as well. Therefore such a nontrivial optimization of the light-field synthesizer parameters is essential for the production of the shortest possible pulses allowed by this sophisticated experimental setup.

Spin dependent electron currents in oscillating fields in solids

In the topic of spin dependent currents in solids the first result we obtained during the project was the description of a two-dimensional semiconductor quantum ring, in which the dynamics of the electrons were controlled by an oscillating Rashba-type spin-orbit interaction. (Note that the significance of this kind of spin-orbit interaction is the fact that its strength can be tuned by external gate voltages, which clearly can be alternating as well.) Our approach was essentially analytic (only evaluation of special functions was done numerically), thus it provided the most possible physical insight into the problem. It was demonstrated that high harmonics of the SOI oscillation frequency appear in the spectrum of spin and charge density oscillations, already with experimentally achievable SOI oscillation amplitudes. Investigating the time evolution of localized wave packets, collapse and revival phenomena, as well as both radial and azimuthal Schrödinger-cat states were shown to appear.

Besides of its physical importance on its own right, the paper [3] played a significant role also from the viewpoint of the whole project, because here we tested the approach based on Floquet’s method, which was found to be useful also later on ([14,18,22]). Returning to Ref. [3], in this case we showed that radial boundary conditions are responsible for the discreteness of the Floquet quasienergy spectrum.

As an extension of our earlier results to more complex systems, we considered a periodic system of quantum wires on the surface of a substrate material [4,5,22]. In these wires, the electrons are confined in two spatial dimensions, they can propagate freely only along the wires.

These wires can form lateral superlattices, which can be produced experimentally. The lattice constant in this case has the order of magnitude of 10 nm, which is large compared to usual interatomic separations in bulk solids. Therefore the energy levels corresponding to this periodic structure are orders of magnitude below the usual band related energies. In other words, the band structure related to the superlattice means a kind of ‘fine structure’ of conventional bands.

The building blocks of the superlattices we considered are narrow, straight line segments. We determined the spin-dependent eigenenergies and the spinor valued eigenfunctions of these line segments, and using appropriate boundary conditions solved the scattering problem for the whole lattice. For an infinite system (when periodic boundary conditions are appropriate), we calculated the corresponding minibands inside the conduction band and have shown that the miniband structure can be controlled by the strength of the spin-orbit interaction. More concretely, we demonstrated that the width (in fact, even the existence) of the mini-bandgaps can be tuned by available experimental techniques. The miniband structure was shown to depend also on the geometrical parameters of the lattice. Having calculated the conductance of finite networks, we found that already relatively small systems (e.g., those containing 7x7 lattice points) exhibit pronounced conductance minima at energies where the infinite system has a bandgap. Based on this observation, flexible, externally tunable filters for the electron energy were proposed.

The calculation of the conductance in Ref. [4] was performed at low temperature, i.e., practically only electrons at the Fermi level took part in the process. However, motivated by the fact that the mini-bandgaps can be “opened” and “closed” by external gate voltages that modify the strength of the SOI, we also investigated the problem at finite temperatures [5]. Note that interference based quantum effects are usually extremely sensitive to thermal fluctuations, and any other dephasing mechanism. However, a significant exception is the band structure of solids, which is clearly of quantum mechanical origin, but provided the characteristic thermal energy is well below the width of the relevant band gap conductance properties are still determined by the band scheme.

We found similar robustness of the miniband structure we obtained in Ref [4]. According to our calculations, until no other transversal mode than the ground state is being excited, the conductance can be strongly modulated by changing the strength of the spin-orbit interaction also at finite temperatures. The reason why we could observe the modulation of the conductance even at relatively high temperatures is that all the mini bandgaps – independently from their position on the energy axis – got closed at the same value of the spin-orbit interaction, and, similarly, they reached their maximal width also at a different, but common value of the control parameter. As an additional test for the robustness of the effects we observed, we introduced point-like scattering centers as a model for impurity scattering. According to our calculations, the observation that spin-orbit interaction can control the conductance is valid even when conductance is strongly suppressed due to scattering events.

As an application of the Floquet’s theory that we adapted to nanoscale systems in Ref. [3], we also calculated the conductance of the superlattices when the spin-orbit interaction has an oscillatory time dependence [22]. We considered quantum mechanical (ballistic) transport with experimentally realizable, sinusoidally oscillating Rashba-type spin-orbit interaction. Transmission peaks were shown to appear in the mini-bandgaps as a consequence of the time-dependent SOI. A detailed analysis showed that this effect is due to the generation of harmonics of the driving frequency, via which e.g., resonances that cannot be excited in the case of static SOI become available. These observations may lead to e.g. narrow band, controllable energy filters.

For simpler geometries, like a single straight line or simple loops, we observed fundamental spin interference effects for oscillating spin-orbit interaction [18]. In this case there are strong, symmetry based ‘no go’ theorems stating that no spin polarization can be achieved for a two-terminal device. However, these argumentations are based on the assumption that time reversal is a symmetry of the system, which is generally not the case for time-dependent Hamiltonians. Indeed, we obtained that oscillating spin-orbit interaction can lead to spin-polarized wave packets that appear even for completely unpolarized input. The spin-orbit interaction that oscillates in a finite domain generates density and spin polarization fluctuations that leave this region as propagating waves. Particularly, spin polarization has space and time dependence even in regions without SOI. Our results were based on an analytic solution of the time-dependent Schrödinger equation. The relevant Floquet quasi-energies that are obtained appear in the energy spectrum of both the transmitted and reflected waves.

Let us note that this effect is general, a slightly weaker version of it can be seen also in lateral superlattices [22].

Relativistic electron transport through an oscillating barrier

As it is known, in the technologically very promising material grapheme, the dynamics of the electrons show a behavior which is analogous to a relativistic Dirac particle. Therefore in [14] we have extended the Floquet technique to the relativistic domain. In this paper transport properties of massive Dirac particles were investigated through an oscillating barrier. The Floquet quasienergies related to the time-dependent potential appear both in transmission and reflection as sidebands around the incoming electron's energy. We took all relevant sidebands into account and presented time averaged transmission and reflection probabilities to describe the quasistationary behavior of the system, in the case of a weakly relativistic, relativistic and ultra-relativistic incident particles. Most qualitative features of scattering on a static barrier -- like Klein paradox -- were still visible, but the transmission probability in the evanescent regime observably increases due to the oscillation of the potential. The strongly inelastic scattering process is shown to lead to multiple Fano resonances. We explained in detail the physical reason for the appearance of these resonances with the coupling of the sideband states generated by the oscillating potential to the bound states of the barrier, and showed the corresponding temporal population trapping in the barrier region. We also presented a detailed study of the time evolution of the wave packets generated in the scattering process. Our results can be relevant for graphene with an induced energy gap, as well as for controlling truly relativistic electrons by electromagnetic pulses.

Optical-field-induced electron current in dielectrics

Our results in this subtopic are related to the interpretation of a recent experiment [Schiffrin et al. Nature Vol. 493 70 (2013)], in which a carrier-envelop-phase (CEP) dependent electric current was generated in an insulator (SiO_2). We considered the motion of charge carriers in a bulk wide-gap dielectric interacting with a few-cycle laser pulse. We have developed [12,13] a semiclassical model based on semiconductor Bloch equations, in which the laser pulse played a double role. It generated electrons in the conduction band (and simultaneously holes in the valence band), and it drove the charge carrier motion between and within the bands. We have also taken into account the scattering effects due to longitudinal optical phonons in the material. We applied this model to describe the emerging time dependent macroscopic currents for laser intensities close to the damage threshold. At such laser intensities, electrons can reach edges of the first Brillouin zone even for electron–phonon scattering rates as high as those known for SiO_2, i.e., dynamical Bloch oscillations can appear even in realistic circumstances. These Bloch oscillations (Bragg-like reflections of electron waves), whenever they happen, affect the dependence of the charge displaced by the laser pulse on its CEP. We have found a qualitative agreement with the experimental findings.

Ultrafast strong-field photoemission of electrons from plasmonic nanoparticles

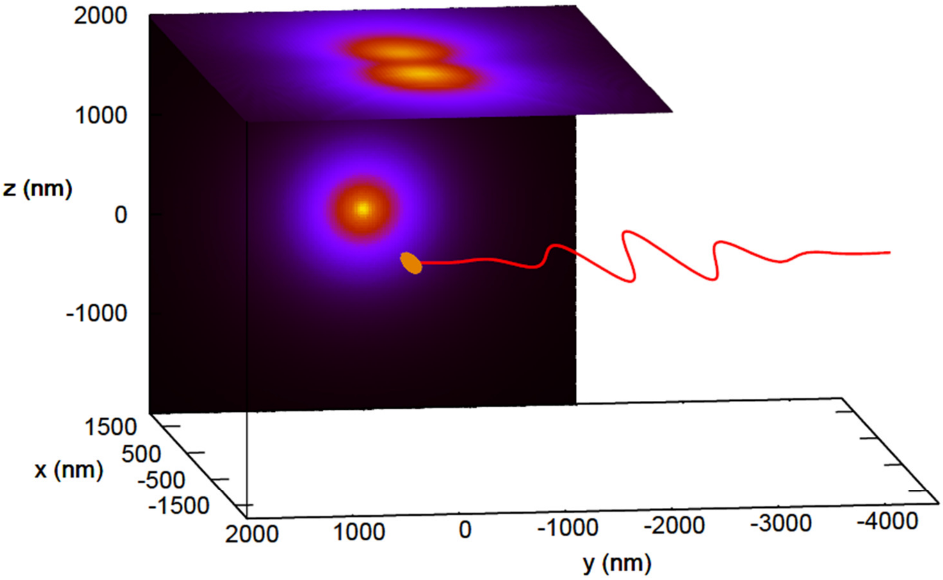
Short, intense bursts of electromagnetic radiation impinging on metallic surfaces induce a photoemission process which is far beyond the traditional picture: both multiphoton and tunneling phenomena can have important role. A number of experiments coupled to the present project [2,6,7,11] have been performed aiming at the investigation of the electron emission, and it has been demonstrated that surface plasmon enhanced electron acceleration plays an important role in the electron spectrum. The carrier-envelope-phase of the exciting laser pulse was shown to play an important role also in these processes.

In Ref [2], an experimental evidence of the generation of few-cycle propagating surface plasmon (SP) polariton wave packets was presented. These ultrashort plasmonic pulses comprised of only 2-3 field oscillations were characterized by an autocorrelation measurement based on electron photoemission. By exploiting plasmonic field enhancement, we achieved plasmon-induced tunneling emission from the metal surface at low laser intensity, opening perspectives for strong-field experiments with low pulse energies.

SP waves were also investigated in the junction of a scanning tunneling microscope (STM) [6]. The SP waves were generated on a 45-nm thin Au film and their near-field was locally probed by the tip of the STM. The temporal structure of the observed tunneling current signal revealed information on the physical mechanisms which regulate the interaction of the electric fields in play. The mapping of the plasmon field to the surface topography delivered experimental evidence for the localization of SP waves in narrow gaps of a few nanometers width and/or at grain boundaries.

Focusing on the electrons, the nonponderomotive nature of ultrafast plasmonic electron acceleration in strongly decaying electromagnetic fields generated by few-cycle and single-cycle femtosecond laser pulses were also investigated [7]. We clearly identified the conditions contributing to nonponderomotive acceleration and established fundamental scaling laws and CEP effects.

When the laser pulse induces photoemission from tailored nanoscale objects, we have demonstrated the ultrafast generation of electrons and unraveled the role of plasmonic field enhancement in this process by comparing resonant and off-resonant particles. We found that electrons become strongly accelerated within the evanescent fields of the plasmonic nanoparticles and escape along straight trajectories with orientations governed by the particle geometry. These results establish plasmonic nanoparticles as versatile ultrafast, nanoscopic sources of electrons.



In the figure above we show a schematic view of the physical process we considered in our work [21]. The laser pulse (represented by the red wave) impinges on a nanoellipsoid (plotted by orange) exciting plasmonic oscillations, which lead to photoemission. The electrons are driven by the net electric field of the incident laser pulse and localized plasmons, and can be detected e.g., at the planes indicated where characteristic electron count distributions are also shown.

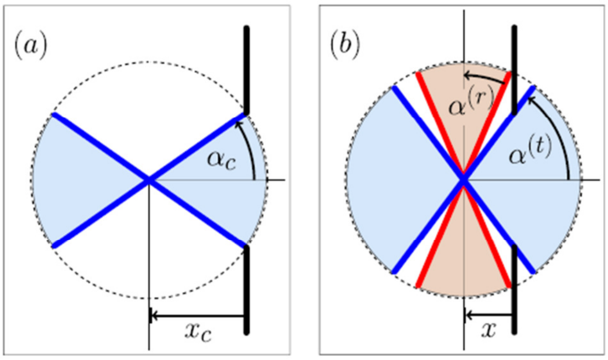
Motivated by the experimental results obtained in [11], in Ref. [21] we considered gold nanoellipsoids as the target of CEP-stabilized ultrashort pulses. The spatial dependence of the emerging net (incoming + plasmonic) electric field was calculated (see Fig. 1), and an interplay was observed between multiphoton and tunneling processes. Our results show considerable field enhancement and few-cycle plasmon oscillations at the same time if the plasmon eigenfrequency is tuned slightly to off-resonance with respect to the laser wavelength. We also calculated the classical trajectories of the photoemitted electrons, and were able to determine their detectable spatial and momentum distributions. We obtained that no visible CEP-dependent effects can be expected for resonant plasmon oscillations, simply because this phase becomes irrelevant for long oscillations containing many optical cycles. In the off-resonant case, however, we have shown that phase-stabilized femtosecond pulses can lead to photoemission from metallic nanospheres with a strong spatial asymmetry.

Dynamics of a specific collective quantum system

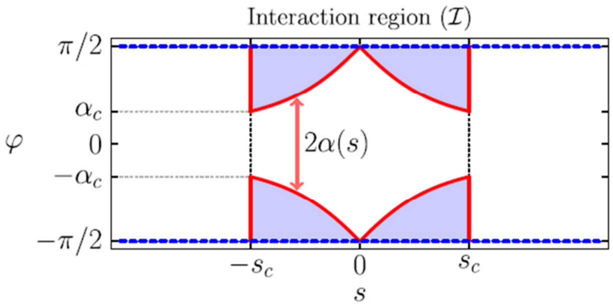
The system of strongly interacting and harmonically trapped one dimensional Bose particles is called a Tonks-Girardeau gas, observed also experimentally with Rb ions. Due to their strong hard-core interaction, the particles of the system exhibit a quasi-fermionic behaviour, and their genuine many body-wave functions (of the ground an excited states) can be explicitly constructed. We have calculated the exact density oscillations of such a system, and proposed a method for the laser spectroscopic observation of these modes without destructing the sample, and to determine thereby quantities characterising the system [1]. The research of this work was intended as a preparation to the techniques used in the main direction of the project.

Scattering of particles with internal structure from a single slit

The scattering of a quantum particle with internal structure is fundamentally different from that of a point like object and may show specific quantum features. We have investigated a relatively simple model, where a rotating linear object a rigid rotor (like a diatomic molecule) passes through an aperture, where the slit size is smaller than the length of the rotor. In our model the centre of mass of the rotor is constrained to move along the symmetry axis perpendicular to the aperture, and the rotation is also constrained around the symmetry axis of the rotor, which is perpendicular to the translational motion.



The figure above shows the geometrical connection between the centre-of-mass position x and the allowable rotation angles, for a classical rotor passing through or reflected from a slit. In (*a*) x_c is the critical distance, and α_c is the corresponding critical angle, where the interaction of the rotor with the slit begins. The allowed domains for the center of mass coordinate and the corresponding angles for reflected (orange) and transmitted (blue) molecules is shown in (*b*). Far from the slit the motion is simple, but for distances smaller than x_c the classical geometric constraint becomes complicated. This results in an interaction region *I* for the angle φ and the reduced coordinate $s{\sim}x$, shown in white in the figure below. We apply the same constraint for the quantum mechanical problem, so we prescribe a vanishing wave function on the boundaries (red line) of the forbidden (blue) region. The wave function is nonzero in the white domains, and the stationary states are the solutions of the two dimensional eigenvalue equation with a Hamiltonian containing the kinetic energies both of translational and rotational motions.



Due to the boundary conditions, the translational and rotational degrees of freedom of the rotor become entangled, and therefore it is impossible to obtain an analytic solution

In order to attack the problem, first a simpler case was considered in [19], where it has been assumed that the object -- coming in from the left – is not rotating, and accordingly it is in the *m=0* eigenstate of the corresponding angular momentum. During the interaction with the aperture, i.e. reaching the *I* domain, however, rotating modes are generated. At sufficiently low energies these modes can be decoupled from each other approximately, and it turns out that the translational motion is similar to a kind of transmission through a potential which can be approximated by a quadratic (harmonic oscillator) function of finite height. At bound state energies of this effective potential, which are necessarily below this height we have found sharp resonances in the transmission.

In the paper [20] we have applied another approach to the solution of the eigenvalue problem, which was technically completely different from the one described above. Here the complicated boundary conditions were taken into account by increasing the region *I* to a larger domain, and the translational and rotational coordinates have been discretized yielding a grid within the emerging box. Then we have determined the Green's function and the S matrix as a function for the incident wave functions with a given energy, that may now contain a rotational part, as well. These objects provide us the energy dependence of the transmission probability, the density of states, as well as the local density of states. We also obtain the total wave function within the interaction region, which means that the whole spectral problem can be solved. The method we use is numerically exact, which means that the only approximation is the choice of the distance between the grid points.

The method of Green's function can be applied at arbitrary energies in contrast to the previous approach based on the approximate analytic procedure where the decoupling of the rotational modes was allowed only at low energies. In the latter case both methods are applicable and they yield almost identical results, which on one hand proves the correctness of the analytic method, and on the other hand serves as a control of the numerical method.

We have classified the sharp resonances occurring in the transmission with respect to their rotational symmetries. They can be interpreted as quasi-bound states appearing at the aperture, and they could be observed in principle in experiments with molecules of sufficiently low velocity at deep temperatures. Our method allows also to determine the lifetimes of these quasi bound states. Although these results do not concern some specific dynamics of electrons, this problem which is presented and solved first in our works [19,20] provides an innovative method, that can be applied in problems of electron scattering on molecules of complicated shapes.

Publications supported by the K81364 OTKA project

[1] Benedict MG; Benedek Cs; Czirják A: ***Exact density oscillations in the Tonks-Girardeau gas and their optical detection***, Optics Express Vol. **18**, 17569-17575, 2010
journal paper: IF 3.278 .

[2] Dombi P; Irvine SE; Rácz P; Lenner M; Kroó N; Farkas G; Mitrofanov A; Baltuska A; Fuji T; Krausz F; Elezzabi AY: ***Observation of few-cycle strong-field phenomena in surface plasmon fields***, Opt. Express Vol. **18**, 24206-24212, 2010
journal paper: IF 3.278

[3] Földi P; Kálmán O; Benedict MG;: ***Two-dimensional quantum rings with oscillating spin-orbit interaction strength: A wave function picture***, Phys. Rev. B **82**, 165322, 2010
journal paper : IF 3.772

[4] Földi P; Szaszkó-Bogár V; Peeters FM: ***Spin-orbit interaction controlled properties of two-dimensional superlattices***, Phys. Rev. B **82**, 115302, 2010
journal paper IF: 3.772

[5] Földi P; Szaszkó-Bogár V; Peeters FM:: ***High-temperature conductance of a two-dimensional superlattice controlled by spin-orbit interaction***, Phys. Rev. B **83**, 115313, 2011
journal paper IF: 3.772

[6] Lenner M; Rácz P; Dombi P; Farkas G, Kroó N:: ***Field enhancement and rectification of surface plasmons detected by scanning tunneling microscopy***, Phys. Rev. B **83**, 205428, 2011
journal paper IF: 3.772

[7] Rácz P; Dombi P:: ***Nonponderomotive electron acceleration in ultrashort surface-plasmon fields***, Phys. Rev. A **84**, 63844, 2011
journal paper IF: 2.861

[8] Benedict MG; Kovács J; Czirják A: ***Time dependence of quantum entanglement in the collision of two particles***, Journal of Physics A, Math Gen, **45**, 085304 2012
journal paper IF: 1.564.

[9] Kovács K, Balogh E., Hebling J., Tosa V., Varju K.: ***Quasi-Phase-Matching High-Harmonic Radiation Using Chirped THz Pulses***, Phys Rev. Lett. **108**, 193903, 2012
journal paper IF: 7.370

[10] Czirjak A, Majorosi S, Kovacs J, Benedict MG: ***Emergence of oscillations in quantum entanglement during rescattering***, PHYS SCR T**153**: 014013 (4pp), 2013
journal paper IF: 1.032.

[11] Dombi P. , Hörl A.,, Rácz P., Márton I., Trügler A., Krenn J.R., Hohenester U:***Ultrafast Strong-Field Photoemission from Plasmonic Nanoparticles***, Nano Letters, **13** (2), pp 674–678, 2013
journal paper: IF: 13.198

[12] Földi P, Benedict MG, Yakovlev VS: ***The effect of dynamical Bloch oscillations on optical-field-induced current in a wide-gap dielectric***, New J. Phys **15**: 063019, 2013 *
journal paper IF: 3. 673

[13] Földi P. , Benedict M.G.: ***Laser driven currents in solids: dynamical Bloch oscillations and phonon scattering,***, Physica Scripta T**153**, 014005, 2013
journal paper: IF 1.023

[14] Szabó L. Zs, Benedict MG, Czirják A, Földi P: ***Relativistic electron transport through an oscillating barrier: Wave-packet generation and Fano-type resonances***, Phys. Rev. B **88**: (7) 075438, 2013 *
journal paper IF: 3.767

[15] Balogh E, Bódi B, Tosa V, Goulielmakis E, Varjú K, Dombi P: ***Genetic optimization of attosecond-pulse generation in light-field synthesizers,*** Phys. Rev. A **90**, 023855, 2014
journal paper IF: 2.997

[16] Ayadi V., Benedict M, Földi P: ***Hidrogénatom gerjesztése és ionizációja rövid lézerimpulzusokkal***, Kvantumelektronika 2014, P26, ISBN 978-963-642-697-2, 2014
abstract

[17]) Czirják A, Majorosi Sz, Hack Sz, Benedict M: ***Optikai alagutazás és kvantumos összefonódottság,***, Kvantumelektronika 2014, E5, ISBN 978-963-642-697-2, 2014
abstract

[18] Szaszkó-Bogár V, Földi P, Peeters FM: ***Oscillating spin-orbit interaction as a source of spin-polarized wave packets in two-terminal nanoscale devices***, J. Phys.: Condens. Matter **26** 135302, 2014
journal paper IF: 2.223.

[19] Shore BW, Dömötör P, Sadurni E, Süssman G, Schleich W.P.: ***Scattering of a particle with internal structure from a single slit***, New J. Phys. Vol. **17**, 013046, 2015
journal paper IF: 3.673

[20] Dömötör P, Földi P, Benedict MG, Shore BW, Schleich W.P.: ***Scattering of a particle with internal structure from a single slit: exact numerical solutions***, New J. Phys. **17**, 023044, 2015
journal paper IF: 3.673

[21] Földi P, Márton I, Német N, Ayadi V, Dombi P: ***Few-cycle plasmon oscillations controlling photoemission from metal nanoparticles***, Applied Physics Letters **106**, 013111, 2015
journal paper IF: 3.515

[22] Szaszkó-Bogár V, Földi P, Peeters FM,: ***Oscillating spin-orbit interaction in two-dimensional superlattices: sharp transmission resonances and time-dependent spin polarized currents***, arXiv:1502.05798, 2015
preprint