MAX-PLANCK-GESELLSCHAFT

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Recollision processes in strong-field QED in the presence of an intense laser beam

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Outline

- Introduction to recollision processes in atomic physics
- Introduction to strong-field QED
- The polarization operator in an intense laser field
- Recollision processes in strong-field QED
- Conclusions and outlook

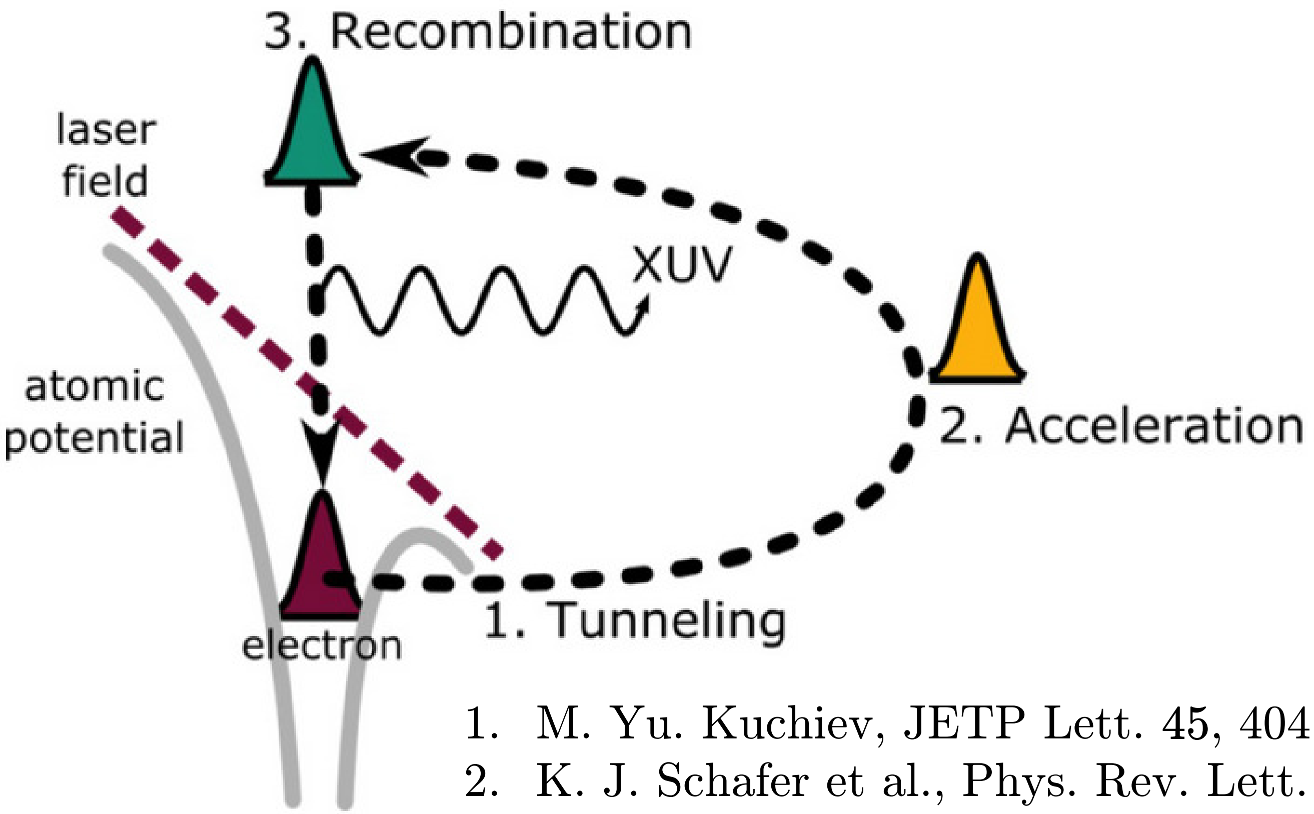
For more information see:

1. S. Meuren, C. H. Keitel, and A. Di Piazza, Phys. Rev. D 88, 013007 (2013)
2. S. Meuren, K. Z. Hatsagortsyan, C. H. Keitel, and A. Di Piazza, arXiv:1407.0188

- Units with $\hbar = c = 1$ will be employed

Recollision processes in atomic physics

- "In a recollision, the oscillating field of a laser pulse causes an electron to accelerate away from an atom or molecule and then, upon reversal of the field, careen back into its parent ion." P. B. Corkum, Physics Today, 2011



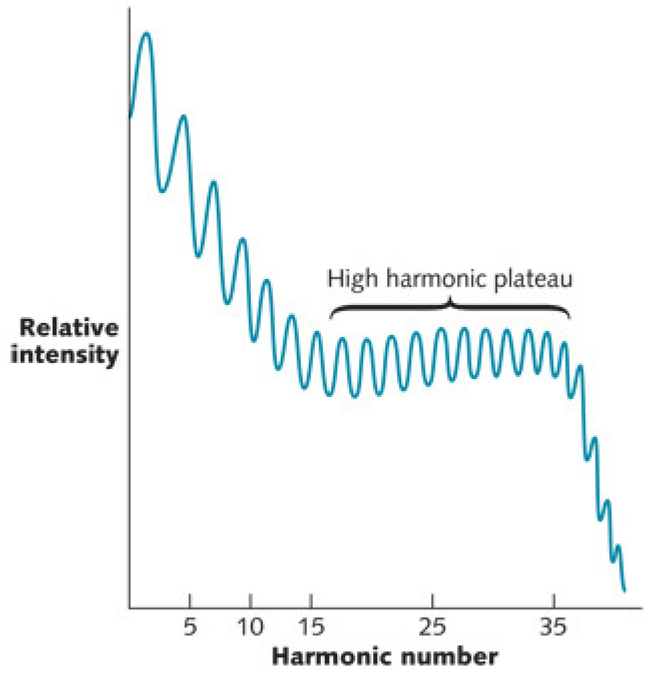
1. M. Yu. Kuchiev, JETP Lett. 45, 404 (1987)
2. K. J. Schafer et al., Phys. Rev. Lett. **70**, 1599 (1993)
3. P. B. Corkum, Phys. Rev. Lett. **71**, 1994 (1993)

- In the process of recollision, the electron recombines with the parent ion by releasing the acquired energy as a high-energy photon (high-harmonic generation) or by striking out another electron (non-sequential double ionization)

- Extension of the harmonic spectrum: $\hbar\omega_M \approx I_p + 3.17U_p$, where $U_p = m\xi^2/4 = e^2 E_L{}^2/4m\omega_L{}^2$

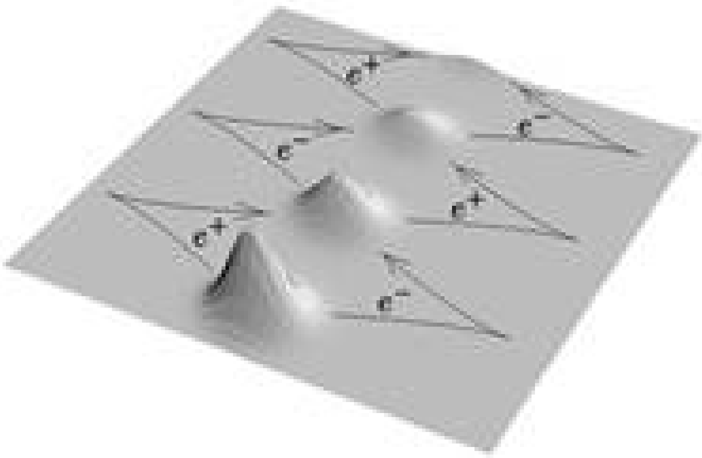
- Scaling of the ratio of the high-harmonic yield in the plateau region and the lowest-order harmonics $1/\xi^{5.5}$ (Frolov et al. PRL 2008)

- In order to produce higher and higher harmonics one would try to go to larger and larger values of ξ

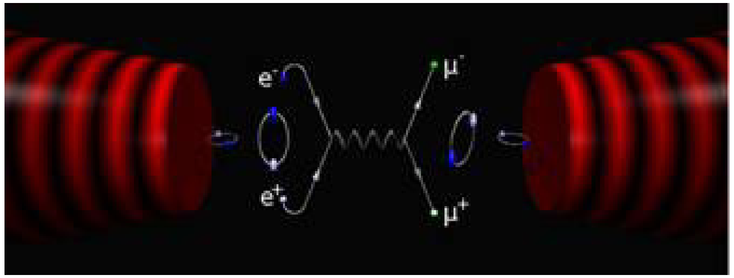


- Atomic recollision processes are suppressed in the relativistic regime: the $(E\times B)$-drift prevents the electron to recombine with parent ion (difference in the charge/mass ration between the nucleus and the electron)

- Using positronium atoms: electron and positron have the same charge/mass ratio and undergo the same relativistic drift (Henrich et al. PRL 2004)
- Problem: wave-packet spreading suppresses the harmonic yield



- A microscopic collider based on laser-driven positronium atoms (Hatsagortsyan et al. EPL 2006, Müller et al. PLB 2008)



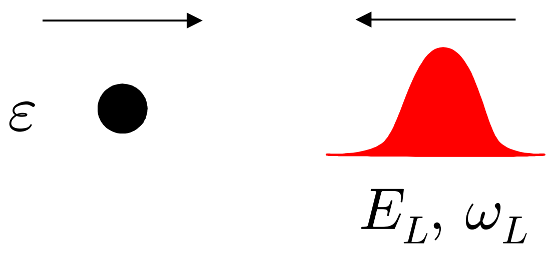
- Production of high-energy particles from the recollision of a laser-accelerated electron-positron pair directly created from vacuum in the presence of the laser field and a nucleus (Kuchiev PRL 2007)
- In PRL 2007 a semiquantitative description of the recollision process is provided, not based on strong-field QED calculations
- How can we describe such recollision processes within the formalism of strong-field QED?

Introduction to strong-field QED

- QED in vacuum is the most successful physical theory we have
- The experimental tests of QED in the presence of strong background electromagnetic fields are not comparably numerous and accurate as in vacuum
- A reason is that the typical fields at which nonlinear QED effects start becoming significant are "large"
- Fields scale of QED:

$$E_{cr} = \frac{m^2c^3}{\hbar|e|} = 1.3 \times 10^{16}\ \text{V/cm}$$
$$B_{cr} = \frac{m^2c^3}{\hbar|e|} = 4.4 \times 10^{13}\ \text{G}$$
$$\Rightarrow \quad I_{cr} = \frac{cE_{cr}^2}{4\pi} = 4.6 \times 10^{29}\ \text{W/cm}^2$$

- An electron with energy ε head-on collides with a plane wave with amplitude E_L and angular frequency ω_L

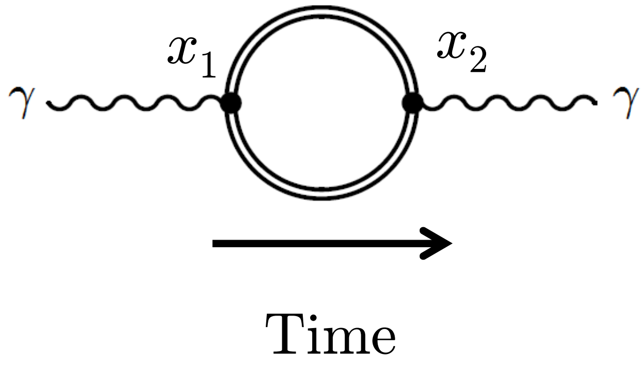


- Relevant Lorentz- and gauge-invariant parameter:

$$\chi = E_L|_{\text{rest frame}}/E_{cr} = 0.59\varepsilon[\text{GeV}]\sqrt{I_L[10^{22}\text{W/cm}^2]}$$

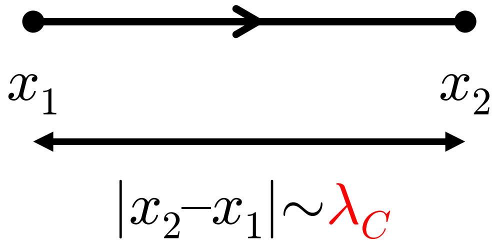
Polarization operator in strong-field QED

- The polarization operator corresponds to the Feynman diagram on the right: a photon transforms at x_1 into an electron-positron pair, which travels through the background field and then annihilates back into a photon at x_2



- The polarization operator seems to be the right object to investigate recollision processes in strong-field QED
- Why has this not been realized so far?
- The propagator in vacuum is

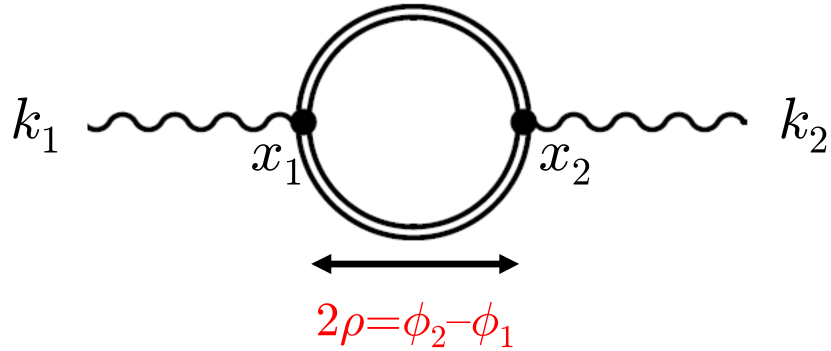
$$G_0(x_2 - x_1) = \int \frac{d^4p}{(2\pi)^4} \frac{\hat{p} + m}{p^2 - m^2 + i\epsilon} e^{-ip(x_2 - x_1)}$$



- The only length/time scale contained in $G_0(x_2-x_1)$ is the Compton wavelength $\lambda_C=1/m=3.9\times10^{-11}$ cm$=1.3\times10^{-21}$ s

Computation of the polarization operator

- The computation of the polarization operator can be reduced to evaluate the amplitude $\Pi(k_1,k_2)$ given by



$$\Pi(k_1, k_2) = \int_{-\infty}^{\infty} d\phi_2\, e^{in\phi_2} \int_0^{\infty} d\rho\, F(\rho, \phi_2) e^{-i\Phi(\rho,\phi_2)}$$

where

  - $2\rho=\phi_2-\phi_1$=phase difference between annihilation and creation points
  - n="number" of laser photons absorbed by the electron-positron pair
  - $F(\rho,\phi_2)$=complicated function not needed here

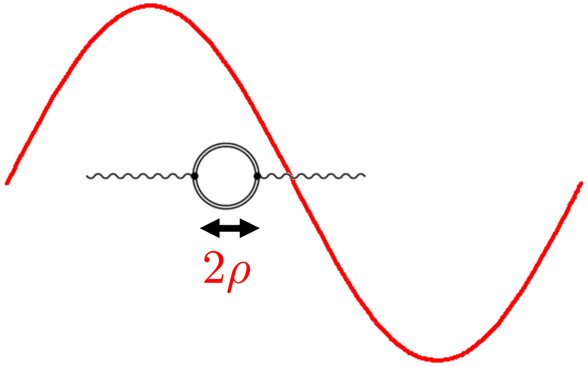
- The phase $\Phi(\rho,\phi_2)$ determines the typical value of n and it reads

$$\Phi(\rho, \phi_2) = \frac{4\xi\rho}{\chi}[1 + \xi^2(J - I^2)]$$

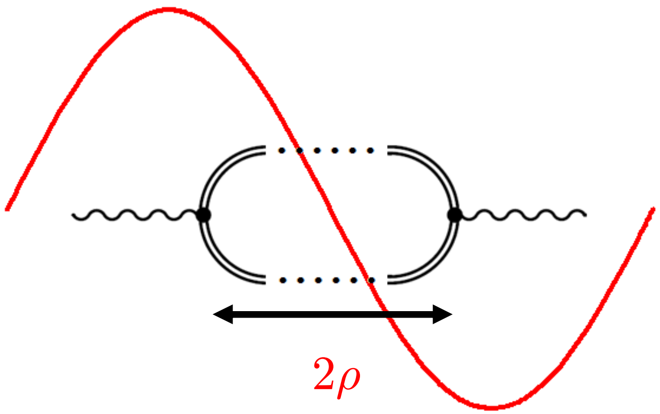
where $\chi=(2\omega_1/m)E_L/E_{cr}$ and I and J are two functions of the laser pulse shape, such that $J \geq I^2$

- At $\xi \gg 1$ and $\chi \lesssim 1$, the phase $\Phi(\rho,\phi_2)$ becomes very large

- The main contribution to the integral in ρ comes from the region of small $\rho=(\phi_2-\phi_1)/2\lesssim 1/\xi\ll 1$, where $\Phi(\rho,\phi_2)\sim 1$
- The dominant "quasistatic" contribution indicates that only a few laser photons can be efficiently absorbed



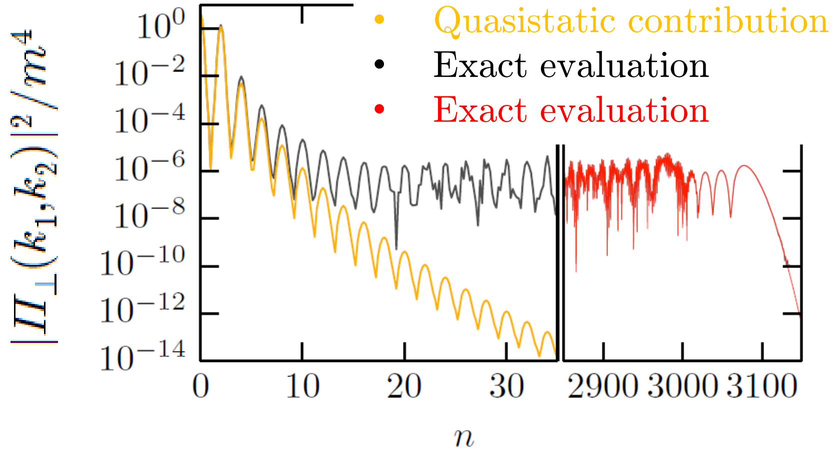
- Look also at the saddle points of $\Phi(\rho,\phi_2)$
- The saddle-point condition coincides with the condition for the recollision of a classical electron and positron created at the same point each with momentum $\boldsymbol{p}=\boldsymbol{k}_1/2$
- They are in the region $\rho=(\phi_2-\phi_1)/2\sim 2\pi$ and the phase at the saddle points is $\Phi(\rho,\phi_2)\sim\xi^3/\chi\sim n\gg 1$
- The electron and the positron propagate for about a cycle in the laser field and absorb a large number of laser photons
- Suppression as ξ^{-6} due to wave-packet spreading



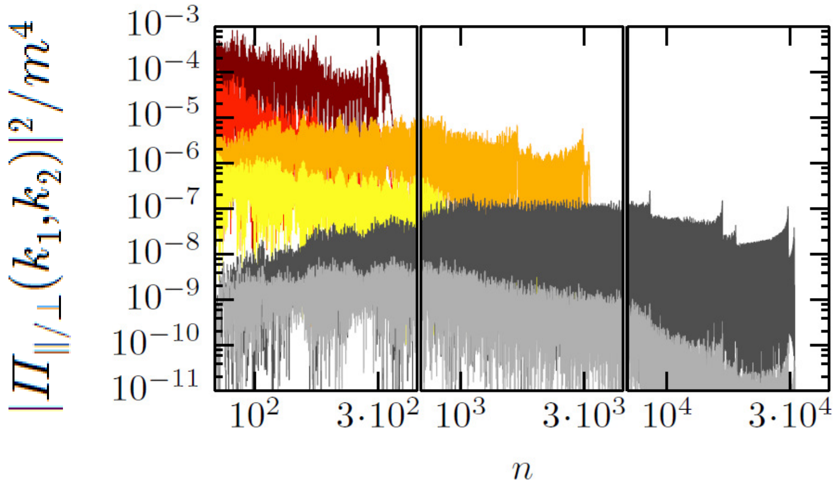
- The maximal energy that the pair can absorb from the laser field: $\omega_M \approx 3.17\xi^3\omega_L/\chi$ exactly corresponds to $2\times 3.17\ U_p$ for an electron-positron pair created with both particles initially at rest

- Numerical example: $\xi=10$, $\chi=1$, 5-cycle, $\sin^2$-laser pulse

- Head-on laser-photon collision
- $\Pi_{\parallel/\perp}(k_1,k_2)$=polarization operator for incoming photon polarized along/perpendicularly to the laser polarization



- Numerical example: $\chi=1$, 5-cycle, $\sin^2$-laser pulse
- $\xi=10^{2/3}\approx 4.6$ ($\perp$ and $\parallel$), $\xi=10$ ($\perp$ and $\parallel$), and $\xi=10^{4/3}\approx 21.5$ ($\perp$ and $\parallel$)
- Height $\sim \xi^{-6}$, cut-off $\sim \xi^3$



Conclusions and outlook

- Recollision processes play a fundamental role in atomic physics
- We have extended the concept of recollision processes to the realm of strong-field QED in intense lasers
- Analogies appear between atomic and strong-field QED photon spectra resulting from recollision processes:

  1. Harmonic yield in the plateau: $\sim\xi^{-6}$
  2. Plateau extension: $\sim\xi^3/\chi$

- The energy absorbed by the electron-positron pair can be exploited to prime new reactions