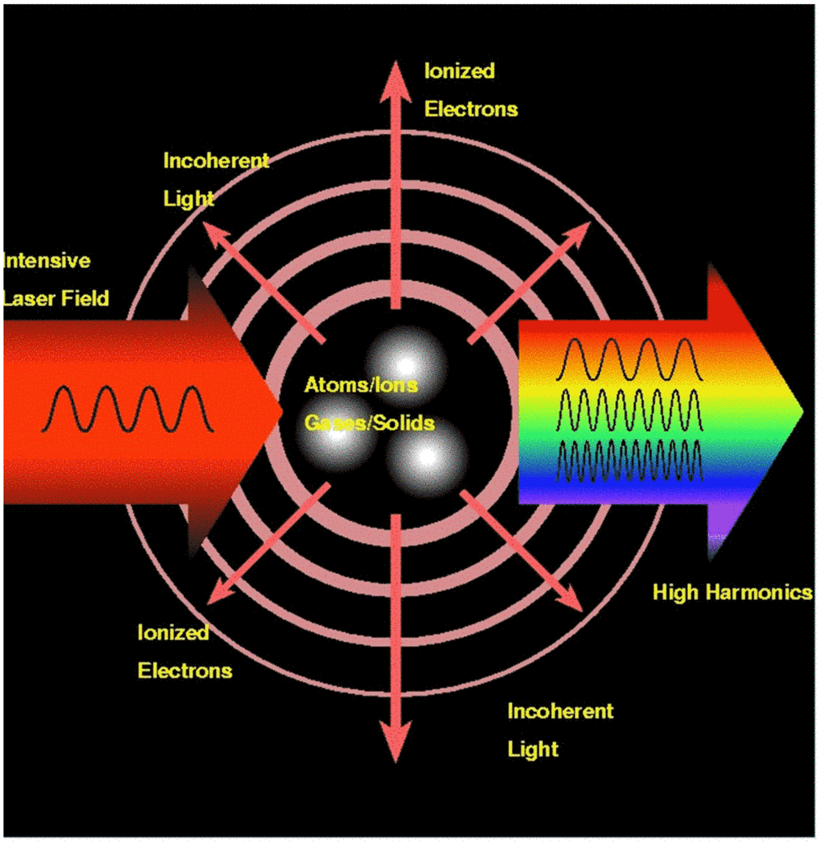
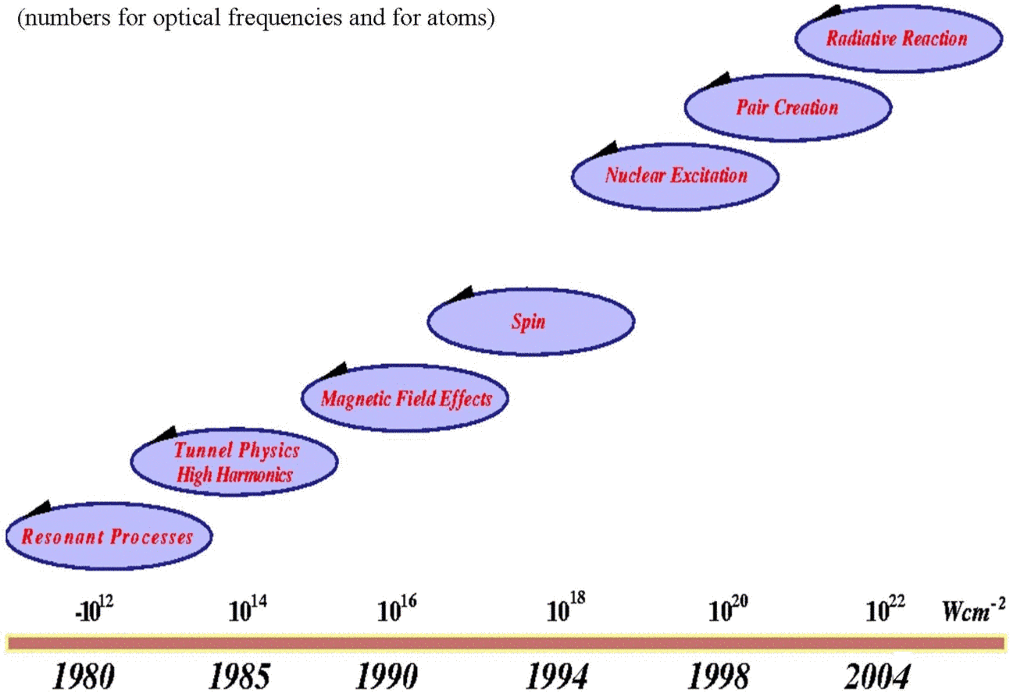


Relativistic quantum dynamics in strong short pulses

Christoph H Keitel
A. Di Piazza
K. Z. Hatsagortsyan
M. Klaiber
C. Müller
Max-Planck
Institute Kernphysik
Heidelberg

Different Physics for Different Laser Intensities

(numbers for optical frequencies and for atoms)



Outline

Brief introduction into relativistic
Laser-Atom Interaction

Laser-induced Quantum Relativistic
Scattering and Bound Dynamics
Attosecond Recollisions

QED & Positronium dynamics with high harmonics & Vacuum nonlinearities

Physics toward the MeV/GeV regime:
Nuclear excitation with XFEL light
Muon production from positronium

Theoretical approaches for atomic systems

Dirac Equation $i\hbar\partial_t\Psi = \left\{c\boldsymbol{\alpha}\cdot\left[\mathbf{p}+\frac{e}{c}\mathbf{A}\right]+\beta mc^2+V\right\}\Psi$

Laser-Driven Atoms: solved numerically in few groups since 1997

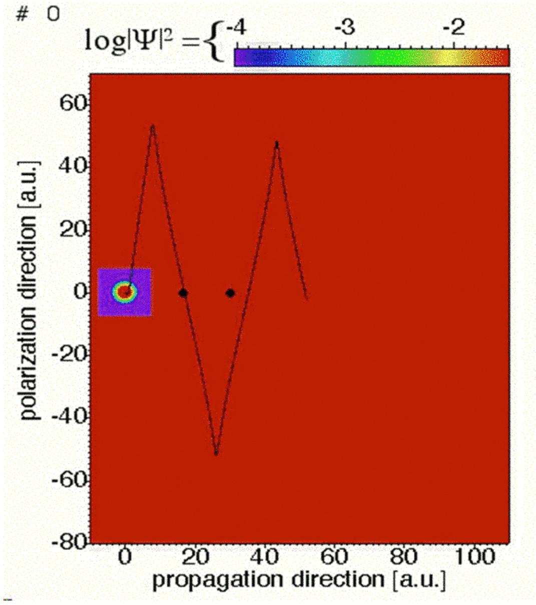
Numerical Challenges: Large Boxes, High Resolution necessary in Time and Space

Alternatives: Klein Gordon (W.Becker, Faisal, Reiss), Schrödinger beyond Dipol, Expansions of Dirac Eq., Classical/Semiclassical Approaches involving Monte Carlo Simulations, Spin (BMT eq.)

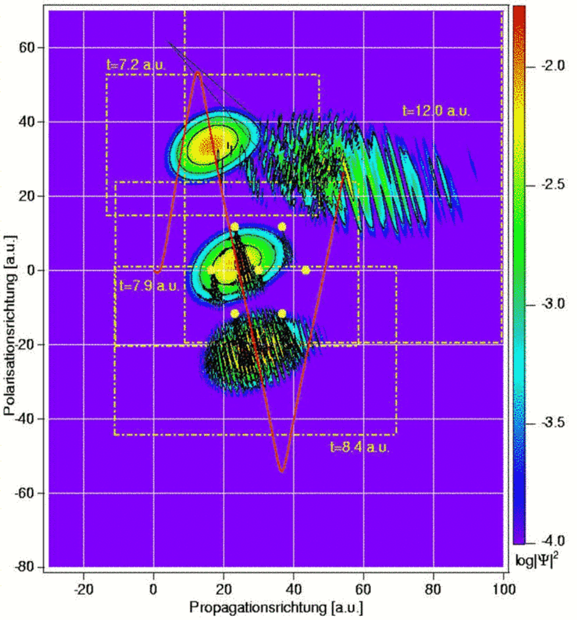
Radiative Reaction (LD) $\frac{d}{dt}\vec{p} = m\frac{d}{dt}\frac{\dot{\vec{r}}}{\sqrt{1-(\dot{\vec{r}}/c)^2}} = \vec{F}_{Laser}+\vec{F}_{Coulomb}$

Multiple scattering in strong laser pulses

Double scattering



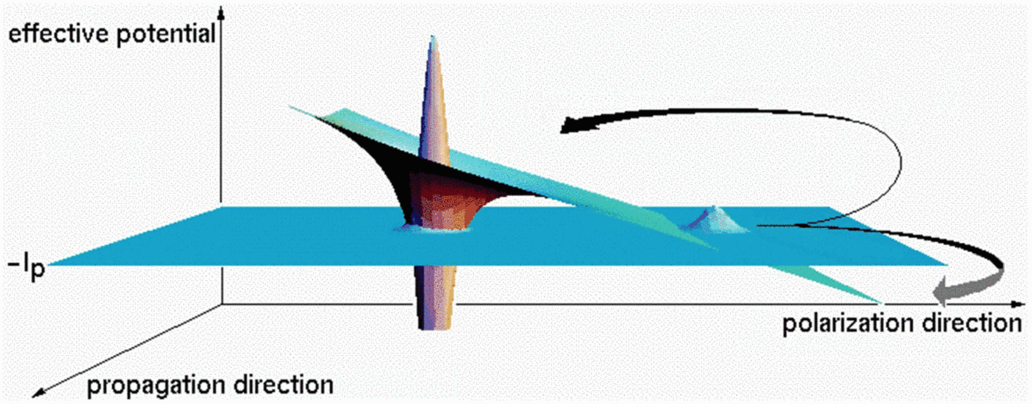
Scattering at 7 ions



E= 50 a.u., w= 1 a.u., ca. 36% speed of light, Sn^{50+}

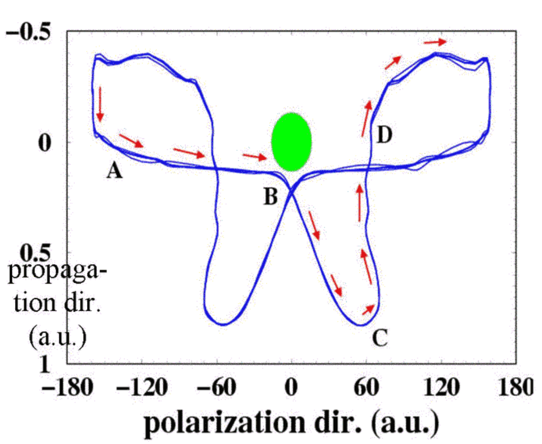
G. Mocken & CHK, PRL (03) & J Comp Phys (04)

Relativistic Tunneling from Ions in extremely intense Laser Fields

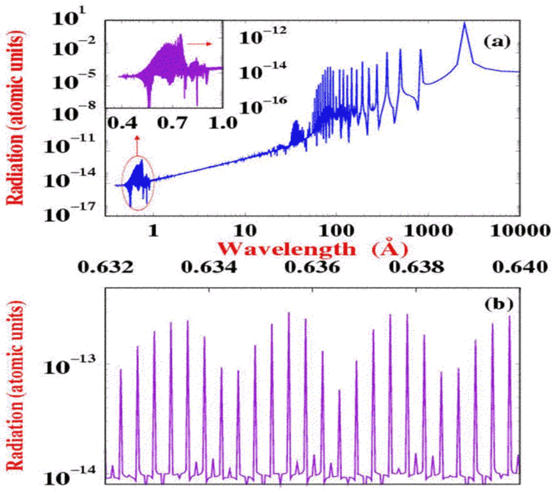


Competition between Lorentz Force and Coulomb Attraction

Substantial tunnel-recollision dynamics possible for moderately relativistic intensities



Center of Mass Motion of the Tunneled Wave Packet



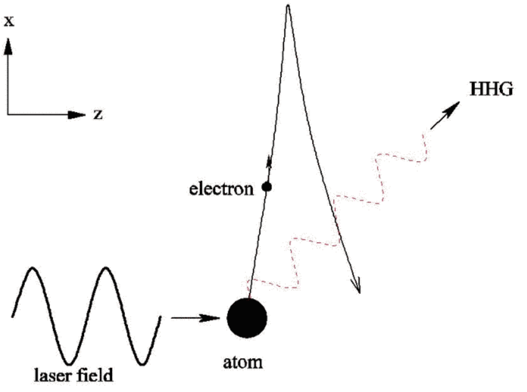
10^{18} W/cm^2

248 nm N^{6+}

Recollions in fully relativistic regime

- laser magnetic field nonnegligible
  →Lorentz-force induced drift of the ionized electron in laser propagation direction
- recollision probability is strongly reduced

→ a simple increase of the laser intensity to produce high energetic HHG is not possible !



Existing attempts to enhance relativistic recollisions

1. Preaccelerated ions that counter-propagate the laser field… G. Mocken et al., J. Phys. B **37**, L275 (2004)

C.C. Chirila *et al.*, Phys. Rev. Lett. **93**, 243603 (2004).

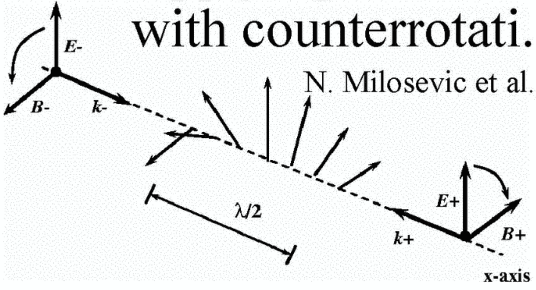
Existing attempts to enhance relativistic HHG

1. Using relativistic ions that counter-propagate the laser field…
2. Using the ionization rescattering process of positronium instead of atoms…

B. Henrich et al., Phys. Rev. Lett.**93**, 013601 (2004).

Existing attempts to enhance relativistic HHG

1. Using relativistic ions that counter-propagate the laser field…
2. Using the ionization rescattering process of positronium instead of atoms…
3. Applying two counterprop. laser beams with counterrotati. circular polarization

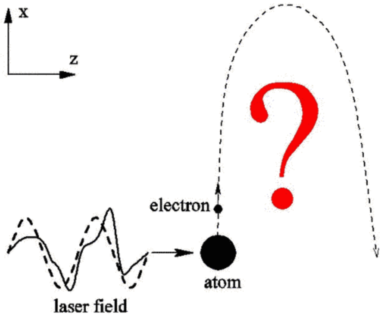


N. Milosevic et al., Phys. Rev. Lett. **92**, 013002 (2004).

Existing attempts to enhance relativistic HHG

1. Using relativistic ions that counter-propagate the laser field…
2. Using the ionization rescattering process of positronium instead of atoms…
3. Applying two counterpropagating laser beams with equally handed circular polarization…

→ ansatz: Changing the shape of
→ the laser field and employing
→ attosecond pulses (with M.
→ Klaiber & K. Hatsagortsyan)



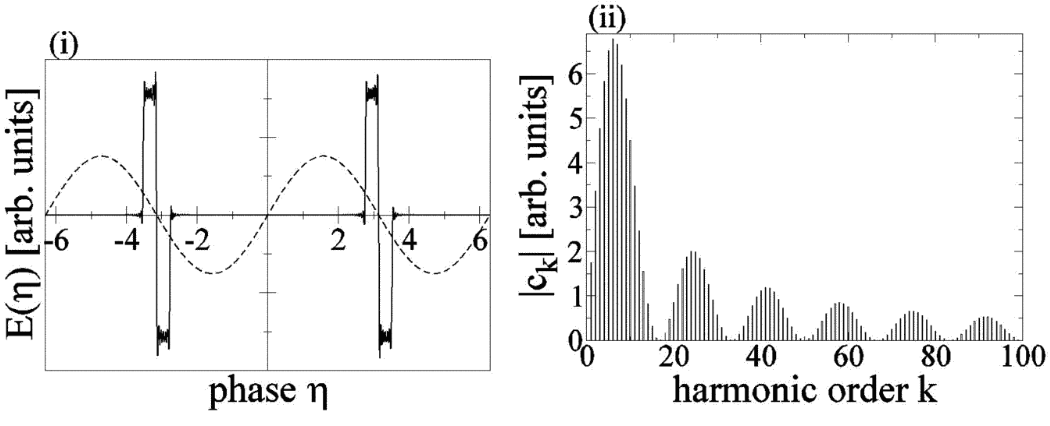
Features of the optimized pulse

- Strong decrease of the laser field after the phase of ionization
  - →concentration of the ionization force on a short time interval.
- long time span with weak laser field strength after ionization
  - → propagation with nonrelavistiv velocity, i.e. no drift
- strong and short pulse before rescattering
  - → concentration of the acceleration force on a short time interval, i.e. fast energy gain, little drift.

Features of the optimized pulse

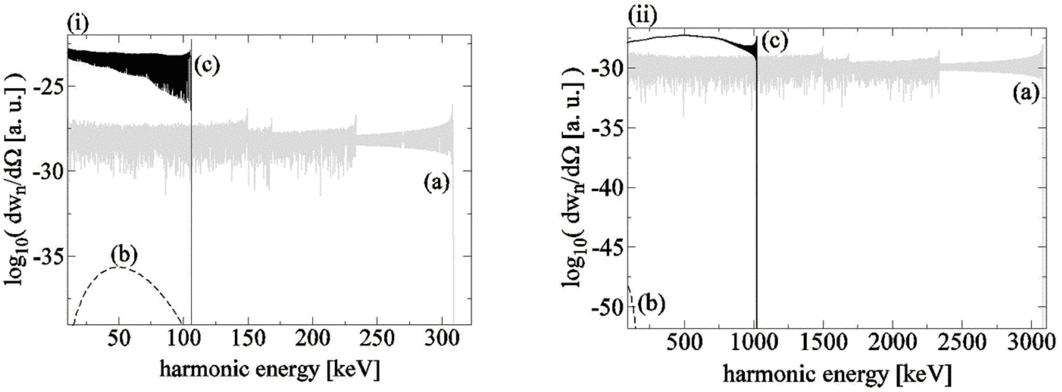
The optimized pulse:

attosecond pulse train with rectangular pulses with a duration of 90 as (laser period 1.5 fs)



HHG Spectra using the tailored pulse

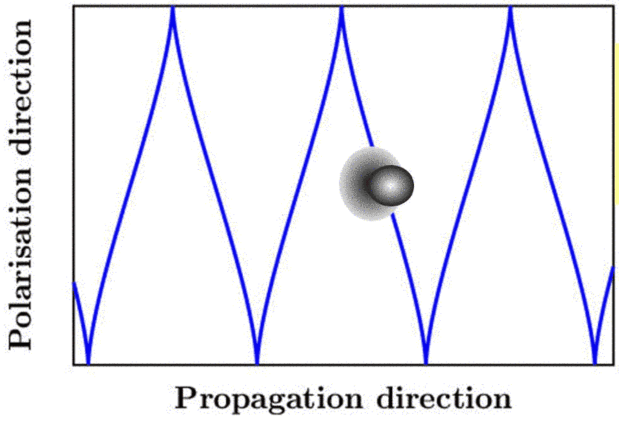
- Moderately relativistic regime:
  - I=5 E 18 W/cm^2, ω=0.1 a.u., $I_p = 28$ a.u.
  - cutoff energy 100keV
- Strong relativistic regime:
  - I=5 E 19 W/cm^2, ω=0.1 a.u., $I_p = 62$ a.u.
  - cutoff energy 1MeV



a) dipole-approximation, sine-pulse; b) relativistic solution, sine-pulse; c) relativistic solution, tailored pulse

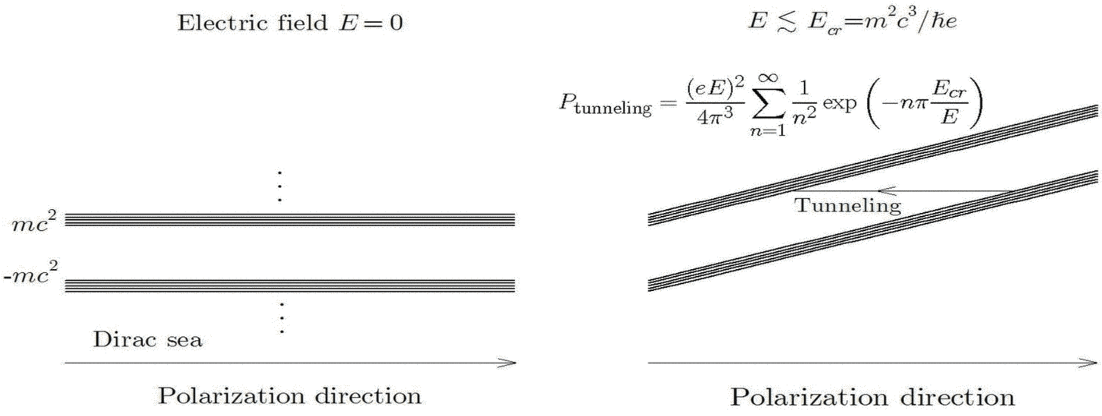
High intensity-QED: Pairs and Radiative Reaction

Pair creation from preaccelerated laser-driven particles:
(Meyerhofer group (1996))



Reabsorption of Initially Emitted Light alters Dynamics (Knight/Maquet groups)

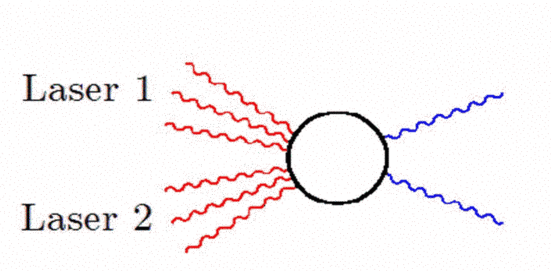
Pair creation with ultra strong laser pulses



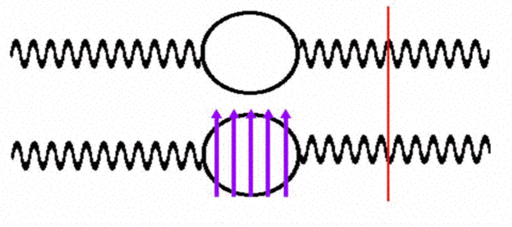
$$P_{\text{tunneling}} = \frac{(eE)^2}{4\pi^3} \sum_{n=1}^{\infty} \frac{1}{n^2} \exp\left(-n\pi \frac{E_{cr}}{E}\right)$$

Further Vacuum Nonlinearities

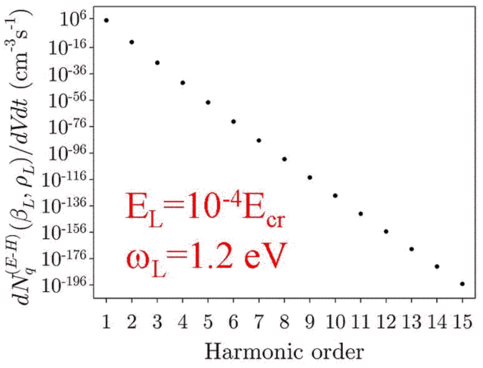
- *Harmonic generation* in vacuum in the collision of two strong laser beams

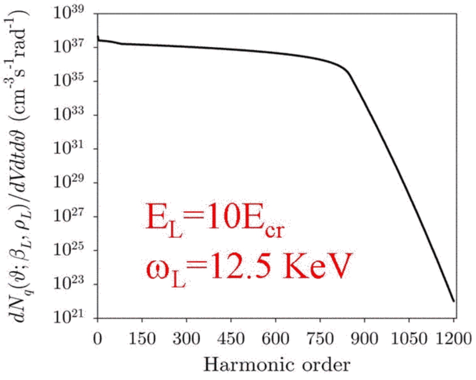


- Vacuum refractive indices in the presence of a strong standing wave



Harmonic generation in vacuum ($E_{cr}=1.3 \cdot 10^{16}$ V/cm)





Can we observe photon-photon scattering nowadays (first harmonic)?
Better to try with three laser collisions (assisted photon-photon scattering)

$$P_{L,min} \simeq 33.5 \left(\frac{\lambda_L}{1\text{ nm}}\right)\left(\frac{\sigma_L}{1\text{ nm}}\right)^{2/3}\left(\frac{1\text{ fs}}{\tau}\right)^{1/3}\left(\frac{1\text{ fs}}{\tau_c}\right)^{2/3}\text{ GW}$$

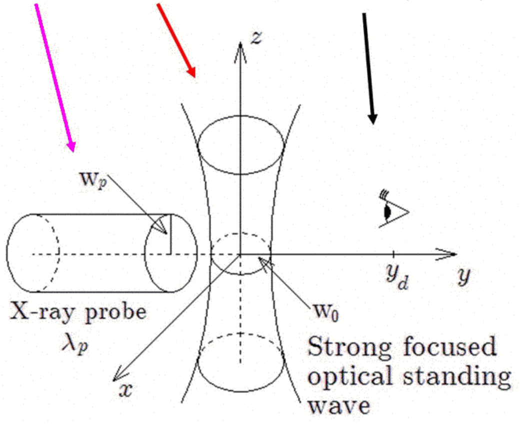
Focused optical laser: $\sigma_L=\lambda_L=1\mu$m, $\tau = \tau_c$ =100 fs

$P_{L,min}$=30 TW !!!

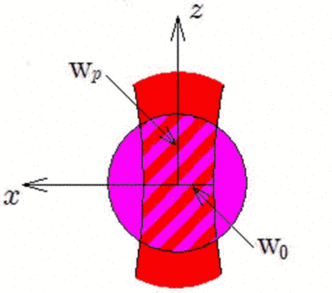
A. Di Piazza et al., PRD
72, 085005 (2005)

Interaction of an X-ray beam with a strong standing wave

$$\mathbf{E}(\mathbf{r},t) \approx \mathbf{E}_p(\mathbf{r},t)+\mathbf{E}_0(\mathbf{r},t)-\frac{1}{4\pi}\int_V d\mathbf{r}'\frac{\mathbf{J}^{(1)}(\mathbf{r}',t-|\mathbf{r}-\mathbf{r}'|)}{|\mathbf{r}-\mathbf{r}'|}$$



Transverse section



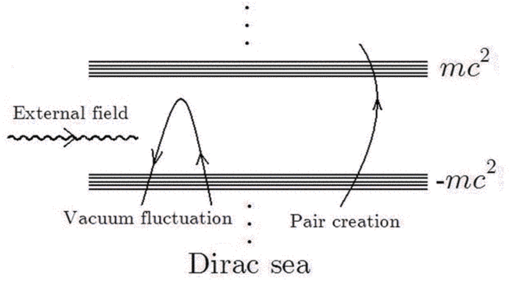
Red: strong field
Violet: Probe field
▨ : Interaction region

Diffraction parameters

- X direction: $\xi_x=(w_0)^2/\lambda_p y_d$
- Z direction: $\xi_z=(w_p)^2/\lambda_p y_d$

For X-ray probes (λ_p=1 nm) and focused optical beams with w_0=1 μm the condition ξ_x>>1 requires y_d<< 1 cm! Diffraction effects have to be taken into account! The strong field intensity has to be large enough that the probe-strong field interaction is detectable ($I_0=10^{25}$-10^{26} W/cm^2, as we will see below)

In the presence of strong field the Maxwell Lagrangian density has to be modified to take into account vacuum fluctuations



$$\mathscr{L} = \frac{1}{2}(E^2 - B^2) + \frac{2\alpha^2}{45m^4}\left[(E^2 - B^2)^2 + 7(\mathbf{E}\cdot\mathbf{B})^2\right]$$

Wave equation in vacuum

Differential form

$$\nabla^2\mathbf{E} - \frac{\partial^2\mathbf{E}}{\partial t^2} = \mathbf{J}(\mathbf{r},t)$$

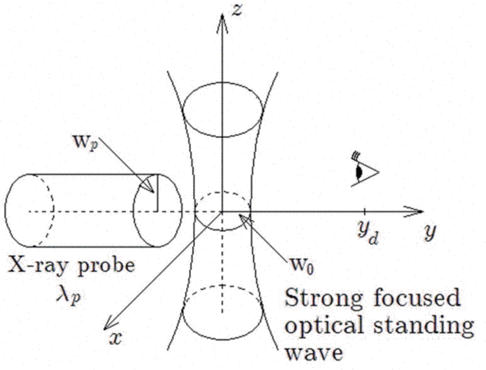
Integral form

$$\mathbf{E}(\mathbf{r},t) = \mathbf{E}_{\text{hom}}(\mathbf{r},t) - \frac{1}{4\pi}\int_V d\mathbf{r}'\frac{\mathbf{J}(\mathbf{r}',t-|\mathbf{r}-\mathbf{r}'|)}{|\mathbf{r}-\mathbf{r}'|}$$

- The quantity **J**(**r**,t) arises because of vacuum fluctuation effects
- **J**(**r**,t) is proportional to $E^3/(E_{cr})^2$ with $E_{cr}=m^2c^3/\hbar e=1.3\times10^{16}$ V/cm
- Generally speaking vacuum corrections are of the order of $(E/E_{cr})^2 \ll 1$

Refractive index description of the interaction

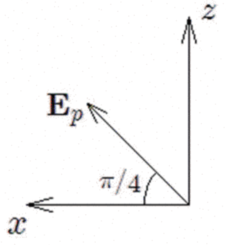
The probe crosses a region $2w_0$ long where the presence of the strong field modifies the vacuum refractive index according to



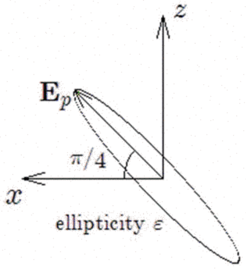
$$n_\parallel = 1 + \sqrt{\frac{\pi}{2}}\frac{7\alpha}{360\pi}\left(\frac{E_0}{E_{cr}}\right)^2$$

$$n_\perp = 1 + \sqrt{\frac{\pi}{2}}\frac{4\alpha}{360\pi}\left(\frac{E_0}{E_{cr}}\right)^2$$

Probe polarization before the interaction



Probe polarization after the interaction

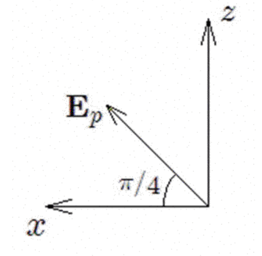


Ellipticity:

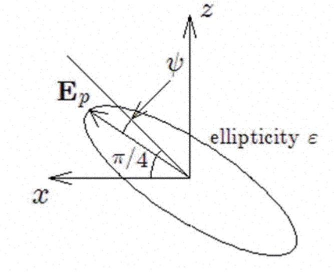
$$\varepsilon = \frac{2\pi w_0}{\lambda_p}(n_\parallel - n_\perp)$$

Results with diffraction:

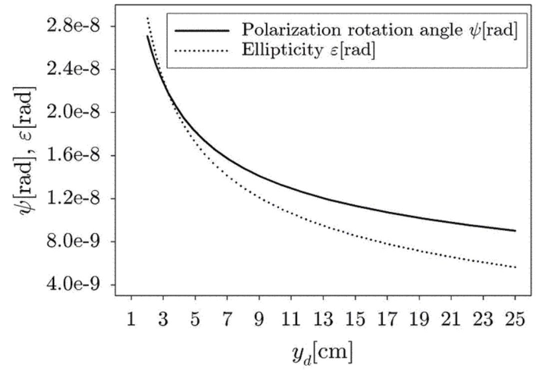
Probe polarization
before the interaction



Probe polarization
after the interaction



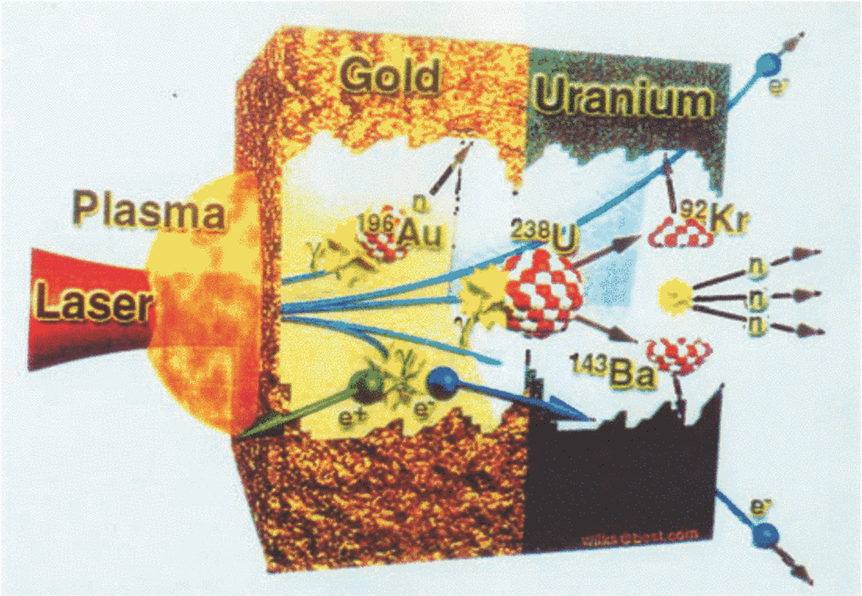
Strong beam: $I_0=10^{23}$ W/cm^2, $w_0=\lambda_0=0.745$ μm
Probe beam: $\lambda_p=0.4$ nm, $w_p=8$ μm
It results: $\xi_x=0.14/(y[\mathrm{cm}])$, $\xi_z=16/(y[\mathrm{cm}])$



- ψ and ε depend on the observation distance y_d
- The PVLAS expected ellipticities are ≈ 5×10^{-11} rad
- The refractive index approach predicts $\psi=0$ and $\varepsilon\approx 4 \times 10^{-7}$ rad (diffraction effects are important!)
- Problems because of low photon statistics can be compensated for with an X-FEL as a probe and a strong field with $I_0=10^{25}$-10^{26} W/cm^2

A. Di Piazza, K. Z. Hatsagortsyan and CHK, hep-ph/0602039
(PRL in press, 2006)

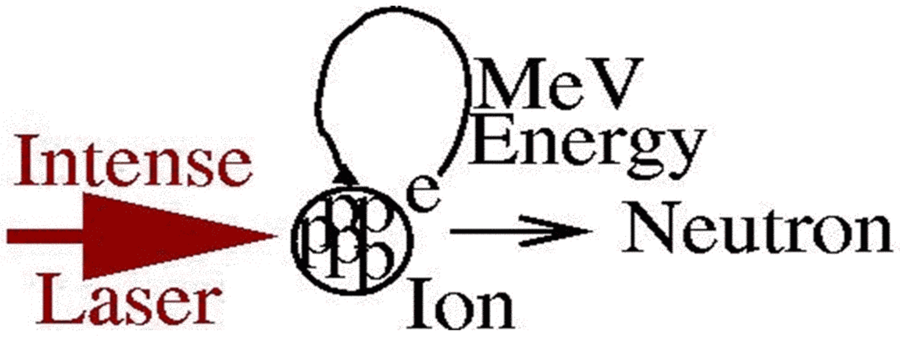
Nuclear Physics via Laser-Plasma Interaction



photonuclear neutrons e.g. by G. Pretzler et al., PRE 58, 1165 (1998), D. Hilscher et al., PRE (2001), K. Ledingham et al., PRL 2000, N. Izuma PRE (2002), G Grillon et al PRL (2002)

Nuclear reactions with bound atomic systems

Nuclear Reactions via Recollisions ?


Intense Laser

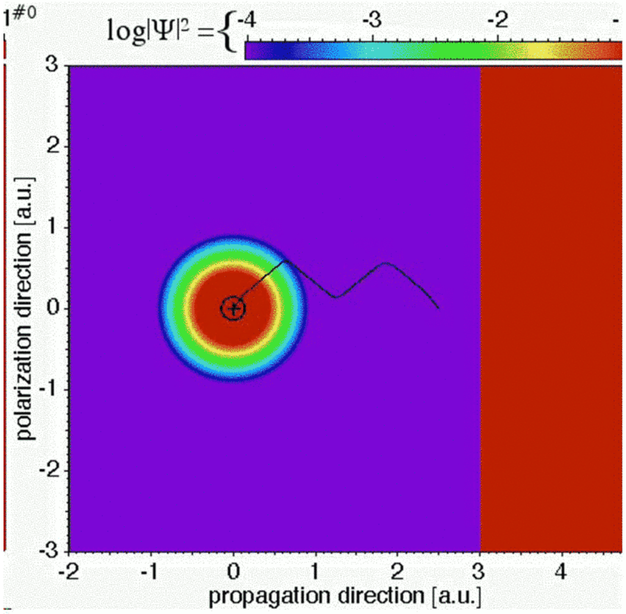
MeV Energy

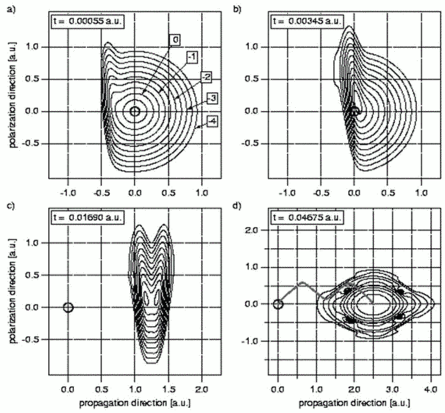
e

Ion

Neutron

Nuclear reactions via preaccelerated ions



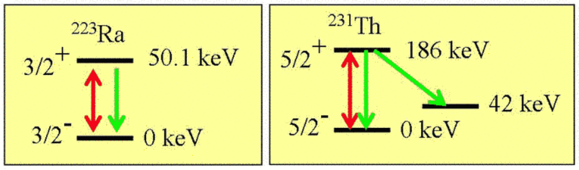


MeV collisions in intense pulses:
Reducing the drift via injecting
the ions against the field

248 nm, 10^{20}W/cm^2 laser pulses
through 7 TeV injection
energy (LHC) of an O^{7+}ion

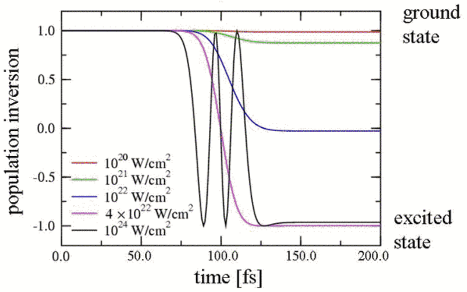
Nuclear quantum optics with x-ray laser pulses

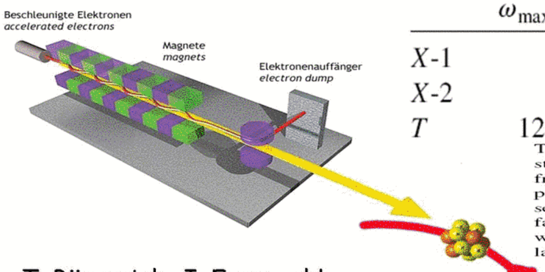
Ultimate goal: enhance preparation, control and detection in nuclear physics with x-ray laser fields



Included: resonant and non-resonant interactions, target acceleration, limited coherence, pulse sequences

Population dynamics (30fs Gaussian pulse in ^{223}Ra)





	$\omega_{\max}$ [eV]	I [W/cm^2]	$\mathcal{B}_{\text{res}}$	I_{res} [W/cm^2]
X-1	56	10^{15}	895	8×10^{20}
X-2	90	10^{16}	557	3×10^{21}
T	12 400	10^{16}–10^{20}	4	2×10^{17}–2×10^{21}

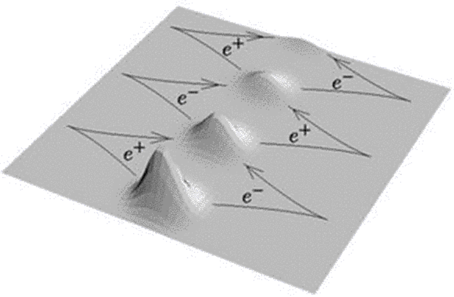
TABLE II. Example laser configurations employed in this study. $\omega_{\max}$ is the maximum photon energy. The laboratory frame intensities I depend on the focussing of the beam. The parameter sets X-1/X-2 are inspired by the GSI XRL facility, the set T by SASE 1 of TESLA XFEL at DESY. $\mathcal{B}_{\text{res}}$ is the required factor $(1+\beta)\gamma$ to match the nuclear rest-frame laser frequency with the transition frequency in ^{223}Ra (see Table I). I_{res} is the laser intensity in this rest frame.

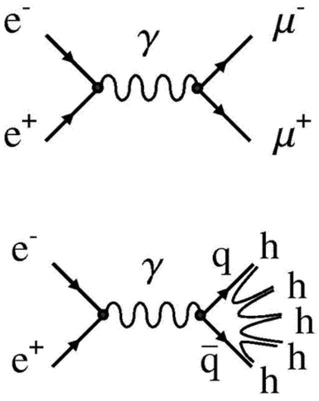
	transition	ΔE [keV]	d [e fm]	$\tau(g)$	$\tau(e)$ [ps]
^{223}Ra	$3/2^- \to 3/2^+$	50.1	0.12	11.435 d	730
^{231}Th	$5/2^- \to 5/2^+$	186	0.017	25.52 h	1030

T. Bürvenich, J. Evers, chk, PRL 96, 142501(2006) (with optical more intense fields: Phys.Rev. C in press)

Laser-driven high-energy e^+e^- collisions

Positronium dynamics in an intense laser field:

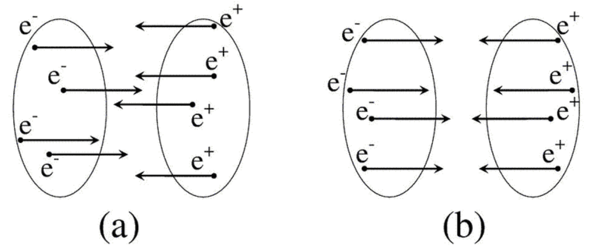




Particle reactions by laser-driven e^+e^- collisions

B. Henrich, K. Z. Hatsgortsyan, chk, PRL 93, 013601 (2004)

Coherent, microscopic e^+e^- collisions



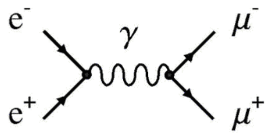
(a) incoherent collisions in conventional collider

(b) coherent collisions in laser-driven collider

coherent luminosity: $$\mathcal{L} = \left[\frac{N_e(N_e-1)}{S_b} + \frac{N_e}{a_\perp^2}\right] f$$

N_e: particle number, S_b: transversal beam area,
$a_\perp$: transversal Ps wave-packet size,
f: bunch repetition frequency

Muons from a laser-driven positronium atom



at today´s highest densities:
1 Ps atom in focal volume

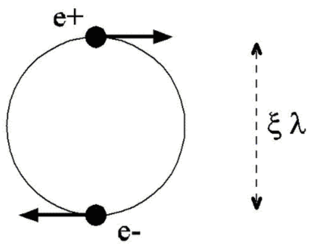
calculate production rate in plane laser wave of circular polarization using Volkov states:

$$R_{\mathrm{Ps}\to\mu^+\mu^-} \approx \frac{\alpha^4}{\xi^2}\left(\frac{a_0}{\lambda\xi}\right)^4 \frac{c}{a_0} \sim 10^{-23}\ \mathrm{sec}^{-1}$$

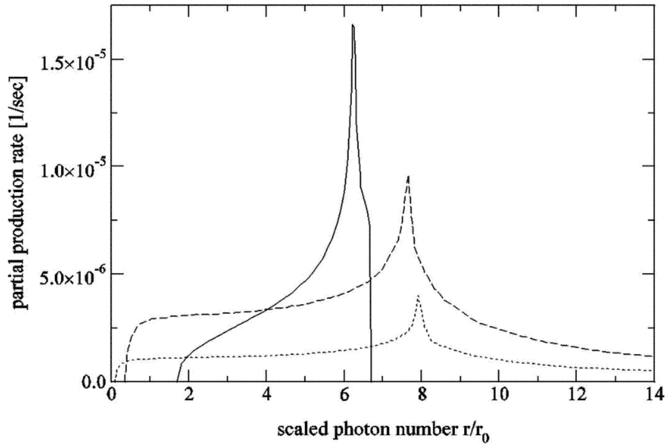
α: finestructure-constant, c: light velocity, a_0: Bohr-radius of Ps λ: wavelength, ξ: intensity parameter ($\xi = eE/mc\omega > \xi_{\min} = 207$, which corresponds to 8×10^{22} W/cm² at λ = 1 μm)

reason for tiny production rate:

in circularly polarized laser no microscopic e+e- collisions (impact parameter ~ ξλ) → better to use incoherent collisions in a laser-driven e+e- plasma



Muons from a laser-driven e^+e^- plasma



total production rate
(= sum over partial rates):

$R \sim 10^7\ \mathrm{sec}^{-1}$

at optimistic plasma density
(10^9 particles in focal volume)

Rate for $\mu^+\mu^-$ creation from an e^+e^- plasma
as a function of absorbed photon number ($r_0 \sim 10^{10}$)
for $\xi = 250$, 500 and 1000 ($I \sim 10^{23}$-10^{24} W/cm^2 at $\lambda = 1\mu$m)

C. Müller, K. Hatsagortsyan, chk, physics/0602106

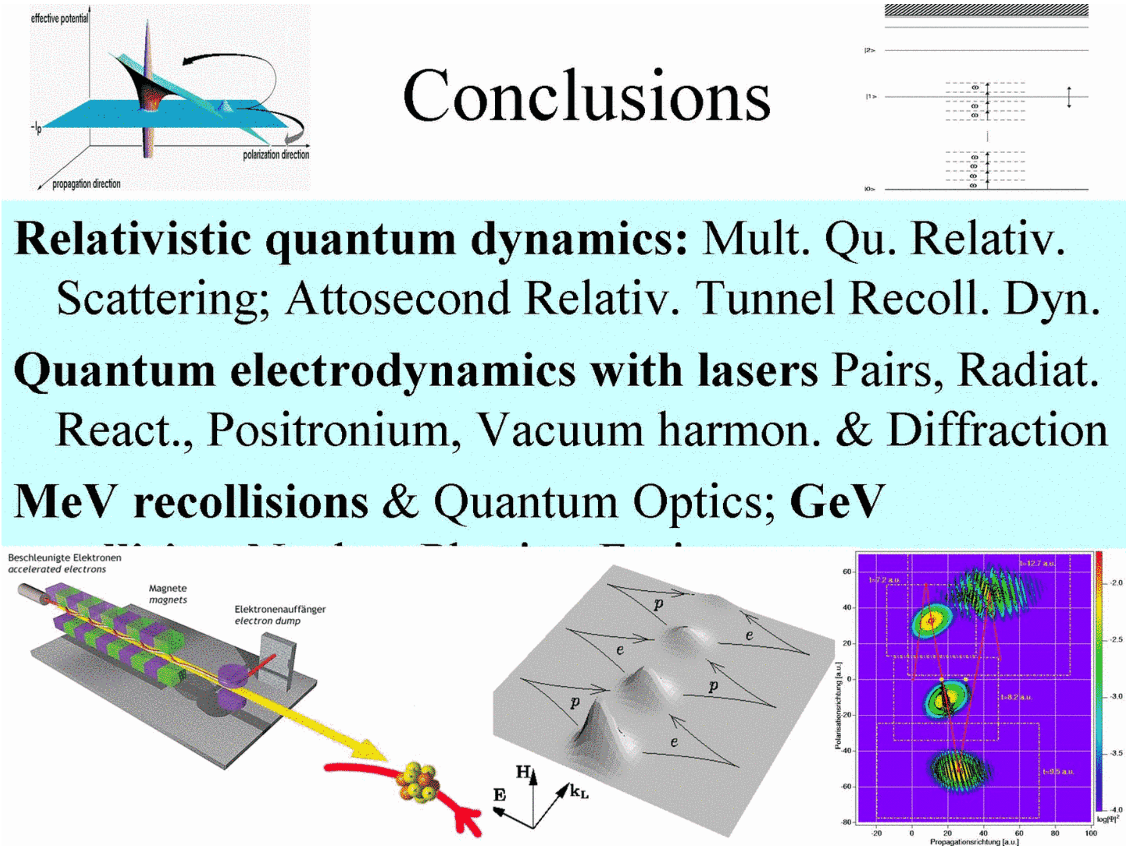
Team in Heidelberg 2005

Key members

Relativistic Quantum Dynamics: Karen Hatsagortsyan & Guido Mocker
(also important: Michael Klaiber and Mario Verschl)

QED & Nuclear Physics: Jörg Evers & Ulrich Jentschura

High Energy Regime: Antonio di Piazza & Carsten Müller



Conclusions

Relativistic quantum dynamics: Mult. Qu. Relativ. Scattering; Attosecond Relativ. Tunnel Recoll. Dyn.

Quantum electrodynamics with lasers Pairs, Radiat. React., Positronium, Vacuum harmon. & Diffraction

MeV recollisions & Quantum Optics; **GeV**