Quantum path interferences in atomic High order harmonic generation

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HHG  XUV source

Spectral range  1-100’s eV  =>  keV  HHG at µm  
OPCPA Fiber laser  
OPA

Efficiency  10⁻⁶ => 10⁻⁴  Long focal  
Phase matching  
quasi-phase matching Optic design  
cells target  
contra-propagation

Spatial and temporal coherences/ small divergence mrad

Envelope duration  fs  
Pulses  as  train or isolated

Control  nm/fs-as  quantum path (QPI)/HHG at µm
Characterisation  fs-as  FROG-CRAB  
RABBITT  XUV-SPIDER

Spatial and temporal coherences  
small divergence mrad  
phase front  XUV-SEASPIDER
Outline

• Classical and quantum approach for HHG description
• Control: Quantum-paths interference QPI
• Experimental set-up
• Analysis through SFA model
• What ‘s next: QPI molecules
HHG in atoms

Atomic potential

1: tunnel ionisation
2: propagation
3: radiative recombination

\[ h\nu_q = I_p + E_c \leq I_p + 3.17U_p \]

Electronic trajectories
→ Several trajectories for the same kinetic energy

E-Field
e- Position

short trajectories
cutoff trajectory
long electron trajectories
driving electric field

e- release
e- recombination

e- release

P. B. Corkum et al., PRL (1993)
Quantum paths

Harmonic phase

\[ \phi_q^{(i)}(t) \approx -U_P \tau_q^{(i)} \approx -\alpha_q^{(i)} I_{\text{Laser}}(t) \]

Harmonic chirp

\[ \Delta \omega_q^{(i)}(t) = - \frac{\partial \phi_q^{(i)}(t)}{\partial t} \approx \alpha_q^{(i)} \frac{\partial I(t)}{\partial t} \]

Phase dependence on the laser intensity

Spectral bandwidth dependence on the intensity gradient

M. Lewenstein et al., PRA (1994)
Macroscopic response

Phase matching

$$\vec{k}_q = q\vec{k}_L(r, z) + \vec{\nabla}\phi_q^{(i)}(r, z, t)$$

Jet position: Control on quantum-paths and phase matching

- Different divergence short/long
  - Spatial selection: Control on path contribution to the detection

Macrosopic HHG emission

P. Salières et al., Science (2001)
Experimental set-up

Pulse IR laser 30 fs
Energy controller

Al filter
platinum grating
gold mirror (acceptance angle 6 mrad)
jet

On-axis spatial selection
Weak divergence

Detection of the short path contribution

Off-axis spatial selection
All divergence

Detection of both path contributions
Position of the filter= control on the contrast
Intensity dependence

ON-AXIS

Argon

Short trajectory

Short and long trajectories

![Graphs showing intensity dependence with laser peak intensity vs harmonic order for short trajectory and short and long trajectories.](image)
Intensity dependence

OFF-AXIS

Argon

Short trajectory

Short and long trajectories
Plateau harmonic (theory)

\[
\alpha_q^{(1)} \approx 1 - 5 \cdot 10^{-14} \frac{\text{rad cm}^2}{W} \\
\alpha_q^{(2)} \approx 20 - 25 \cdot 10^{-14} \frac{\text{rad cm}^2}{W}
\]

Periodicity of order 1:

\[
\frac{2\pi}{\Delta \alpha} \approx 0.3 - 0.4 \cdot 10^{14} \frac{W}{\text{cm}^2}
\]

First order interferences 10’s as control!!!
Macroscopic response

Propagation and macroscopic calculation SFA
Argon
H15

ON-AXIS
Short trajectory

OFF-AXIS
Short and long trajectories
QPI: limitation

**Xenon**

Low $I_p$ (12.1 eV)
(barrier suppression at $8.7 \cdot 10^{13}$ W/cm²)

→ depletion
→ blue shifted

**Argon**

Mid $I_p$ (15.8 eV)
(barrier suppression at $2.5 \cdot 10^{14}$ W/cm²)

→ depletion

**Neon**

high $I_p$ (21.6 eV)
(barrier suppression at $8.6 \cdot 10^{14}$ W/cm²)

→ no limitation
Distinction of QP

“Frequency- like analysis”

\[
x_q(I) = \sum_j |x_q^{(j)}| e^{-\alpha_q^{(j)} I}
\]

\[
x_q(I, I_0) = \sum_j |x_q^{(j)}| e^{-\alpha_q^{(j)} I} \times W(I - I_0)
\]

\[
x_q(\alpha, I_0) = FT[x_q(I, I_0)]
\]

\[\alpha_q^{(1)} = 5\]

\[\alpha_q^{(2)} = 25\]
Conclusion

First order quantum path interferences observed experimentally

Study of the QPI as a technique -> atomic dipole phase extraction

High order interferences access through direct spectral measurements

Exploring more complicated target: diatomic molecules

A. Zaïr et al PRL 100, 143902 (2008)
M. Holler et al OE 17, 5716 (2009)
People

A. Zaïr, M. Holler, A. Guandalini, F. Schapper, J. Biegert, L. Gallmann and U. Keller

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Thank you!!!