# The Nobel Prize in Physics 2023

**“for experimental methods that generate attosecond pulses of light for the study of electron dynamics in matter”**

Pierre Agostini

Ferenc Krausz

Anne L’Huillier

Andreas Hoffmann
12.10.2023

# Outline

**1 What is an attosecond?**

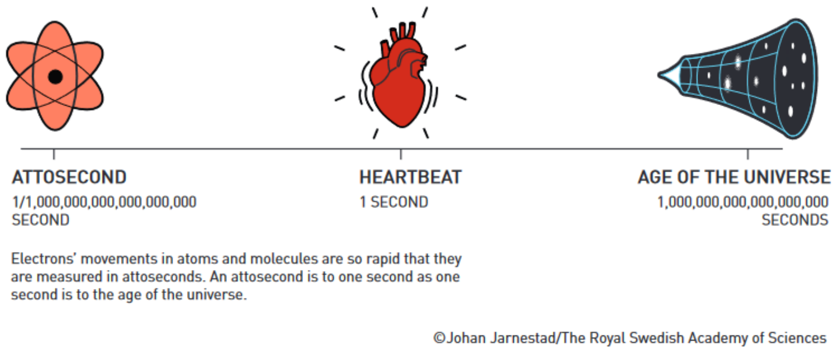
**2 How to generate attosecond pulses?**

- High Harmonic Generation
- Attosecond pulse trains
- Isolated attosecond pulses

**3 How to measure attosecond pulses?**

**4 Nobel Laureates' contributions**

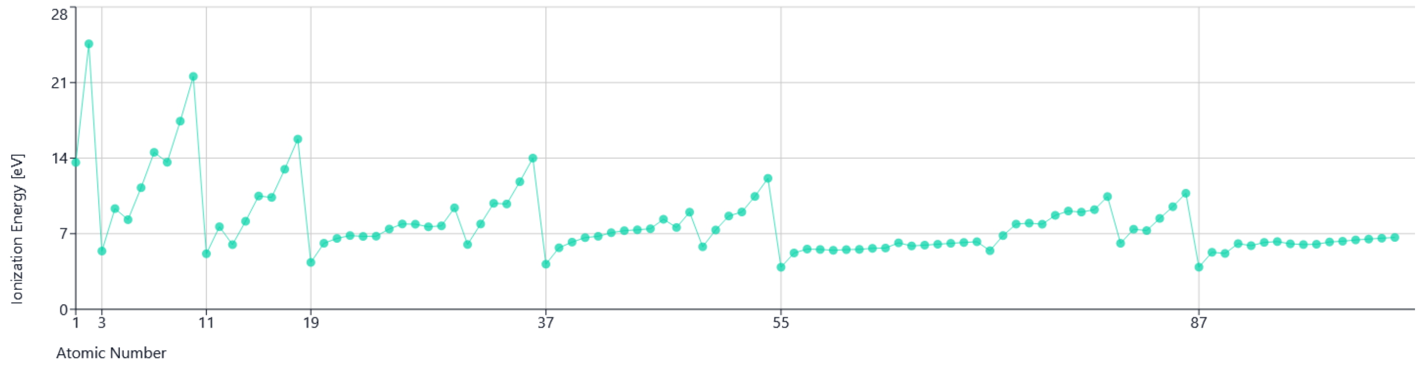
# What is an attosecond?

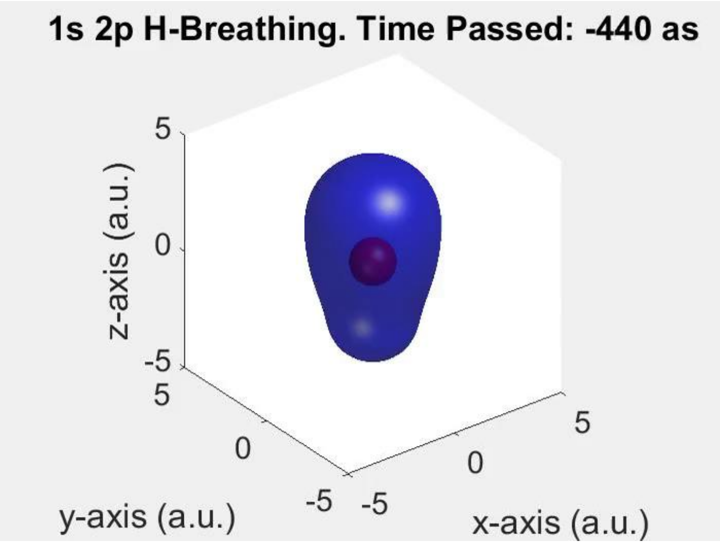



The natural time scale of electron motion in atoms, molecules, and solids is the attosecond (1 as= $10^{-18}$ s).

$$T_C = \frac{h}{E_1 - E_0} = \frac{4.135 \cdot 10^{-15} eV \cdot s}{E_1 - E_0}$$

For 10 eV : 413 as

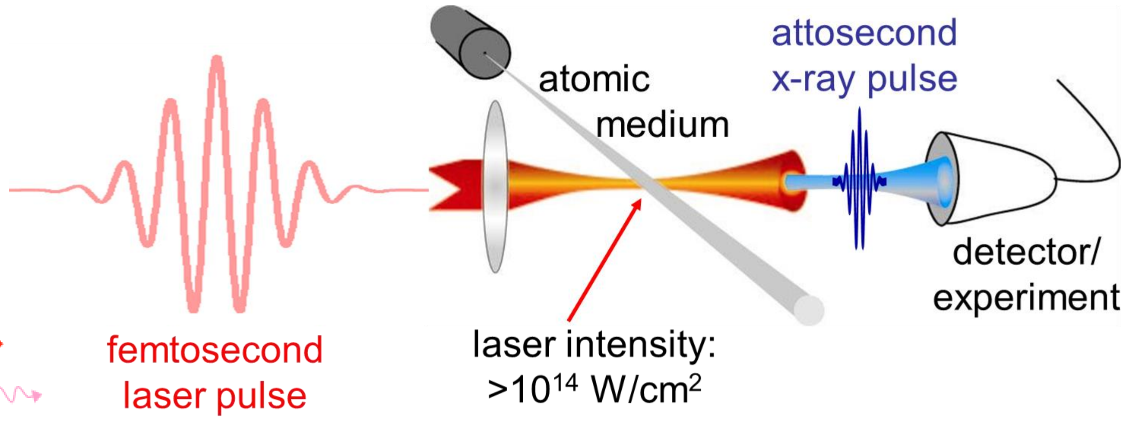


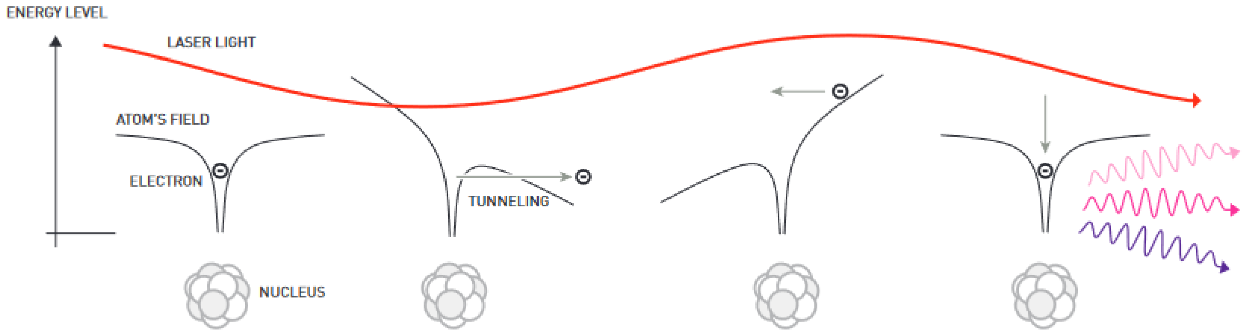

What is the time scale of photoionization? How does the ionization work in multielectron systems? Are the ionization channels direct or indirect? How do electrons regroup during ionization?

# How to generate attosecond pulses?

## High Harmonic Generation




Simple Man‘s model




1 An electron that is bound to an atom's nucleus cannot normally leave its atom; it does not have enough energy to lift itself out of the well created by the atom's electrical field.

2 The atom's field is distorted when it is affected by the laser pulse. When the electron is only held by a narrow barrier, quantum mechanics allow it to tunnel out and escape.

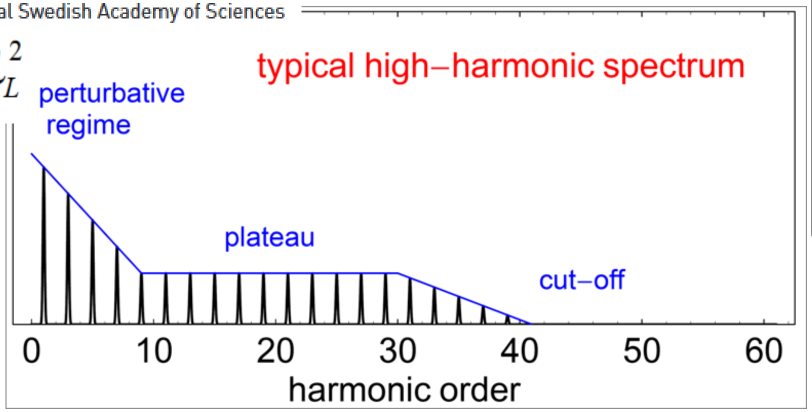
3 The free electron is still affected by the laser field and gains some extra energy. When the field turns and changes direction, the electron is pulled back in the direction it came from.

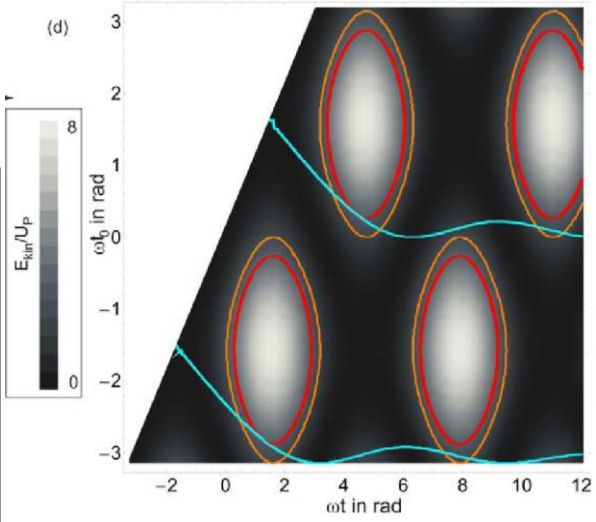
4 To reattach to the atom's nucleus, the electron must rid itself of the extra energy it gained during its journey. This is emitted as an ultraviolet flash, the wavelength of which is linked to that of the laser field, and differs depending on how far the electron moved.



$$E_{max} = q_{max}\cdot\hbar\omega = I_P + 3.17\cdot U_P \qquad U_P = \langle E_{kin}\rangle_T \propto I\cdot\lambda_L^2$$

$$\Delta k = q\cdot k(\omega_L) - k(q\cdot\omega_L) = \Delta k_{Disp.} + \Delta k_{Plasma} + \Delta k_{Geom.}$$



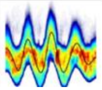



# How to generate attosecond pulses?

## Attosecond pulse trains and isolated pulses

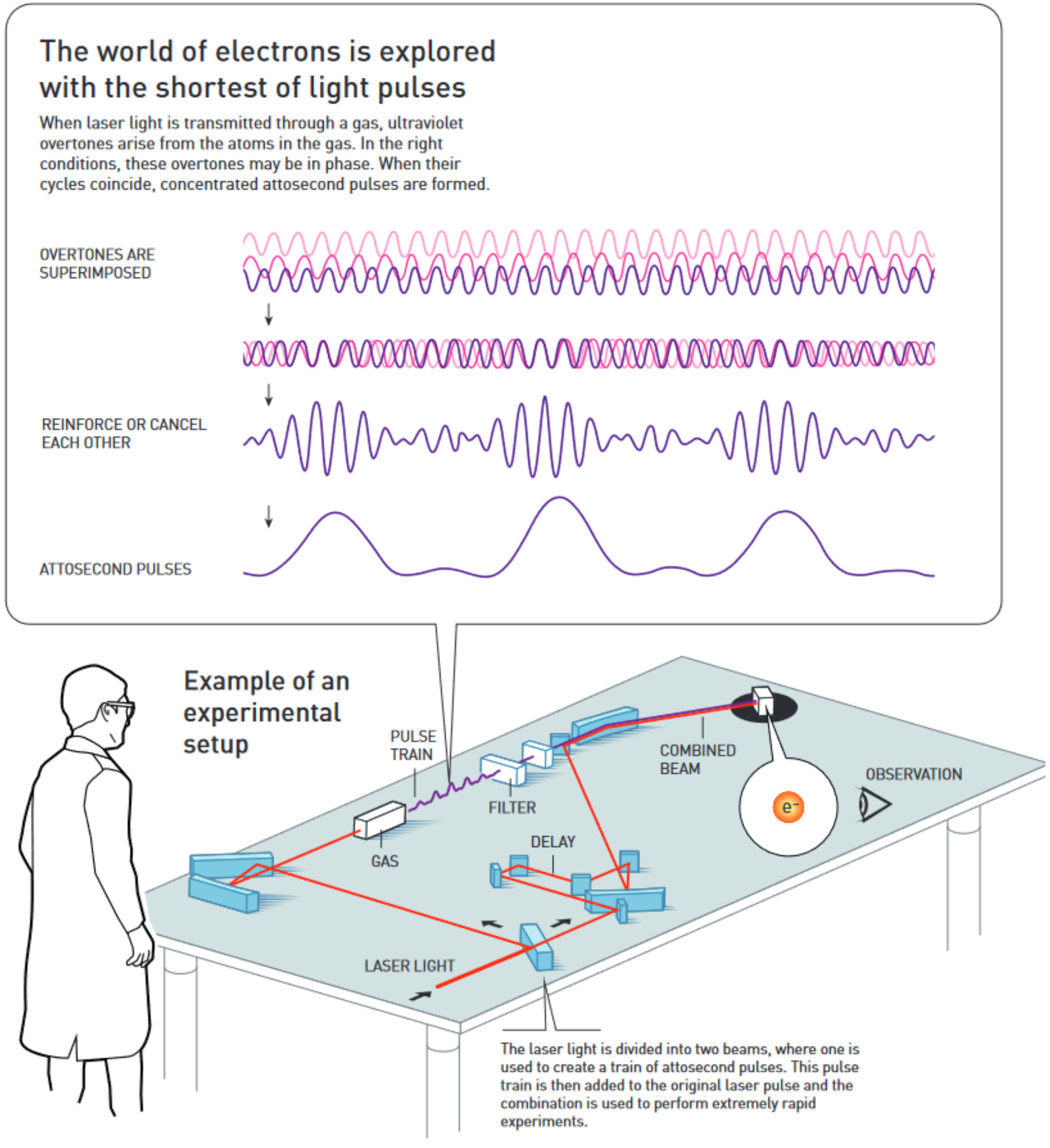
- Harmonics are emitted every half-cycle of the driving laser pulse
- Proper focusing in the gas medium allows selection of the trajectories
- If the harmonics are in phase an attosecond pulse is formed which is repeated every half-cycle of the driving laser pulse
- The pulse duration of the driving laser should be as short as possible to have a few half-cycles contribute as possible to generate short APT
- Isolated attosecond pulses can be generated near the cutoff by spectral filtering or more advanced techniques
- Current world record: 43 as

Optics Express Vol. 25, Issue 22, pp. 27506-27518 (2017) • https://doi.org/10.1364/OE.25.027506



Streaking of 43-attosecond soft-X-ray pulses generated by a passively CEP-stable mid-infrared driver

Thomas Gaumnitz, Arohi Jain, Yoann Pertot, Martin Huppert, Inga Jordan, Fernando Ardana-Lamas, and Hans Jakob Wörner

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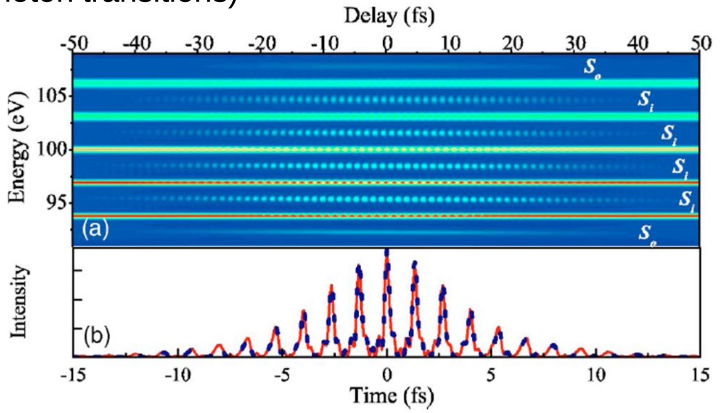
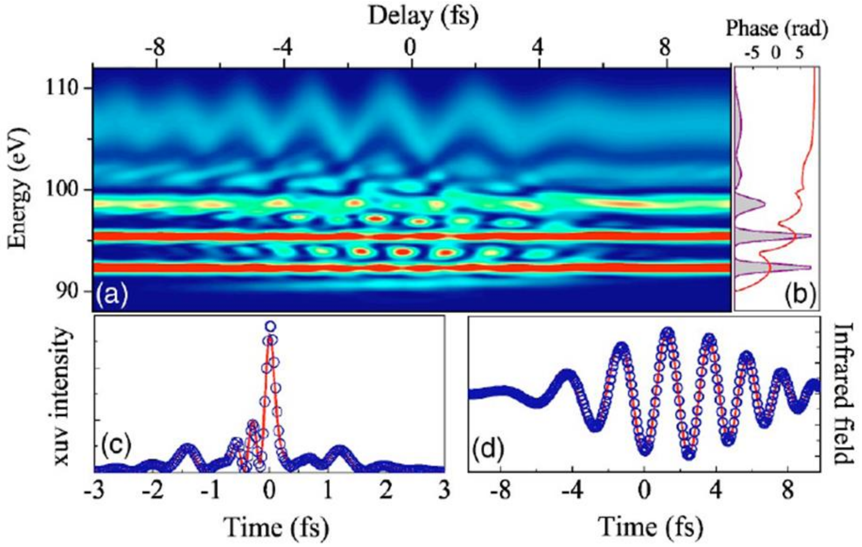
# How to measure attosecond pulses?

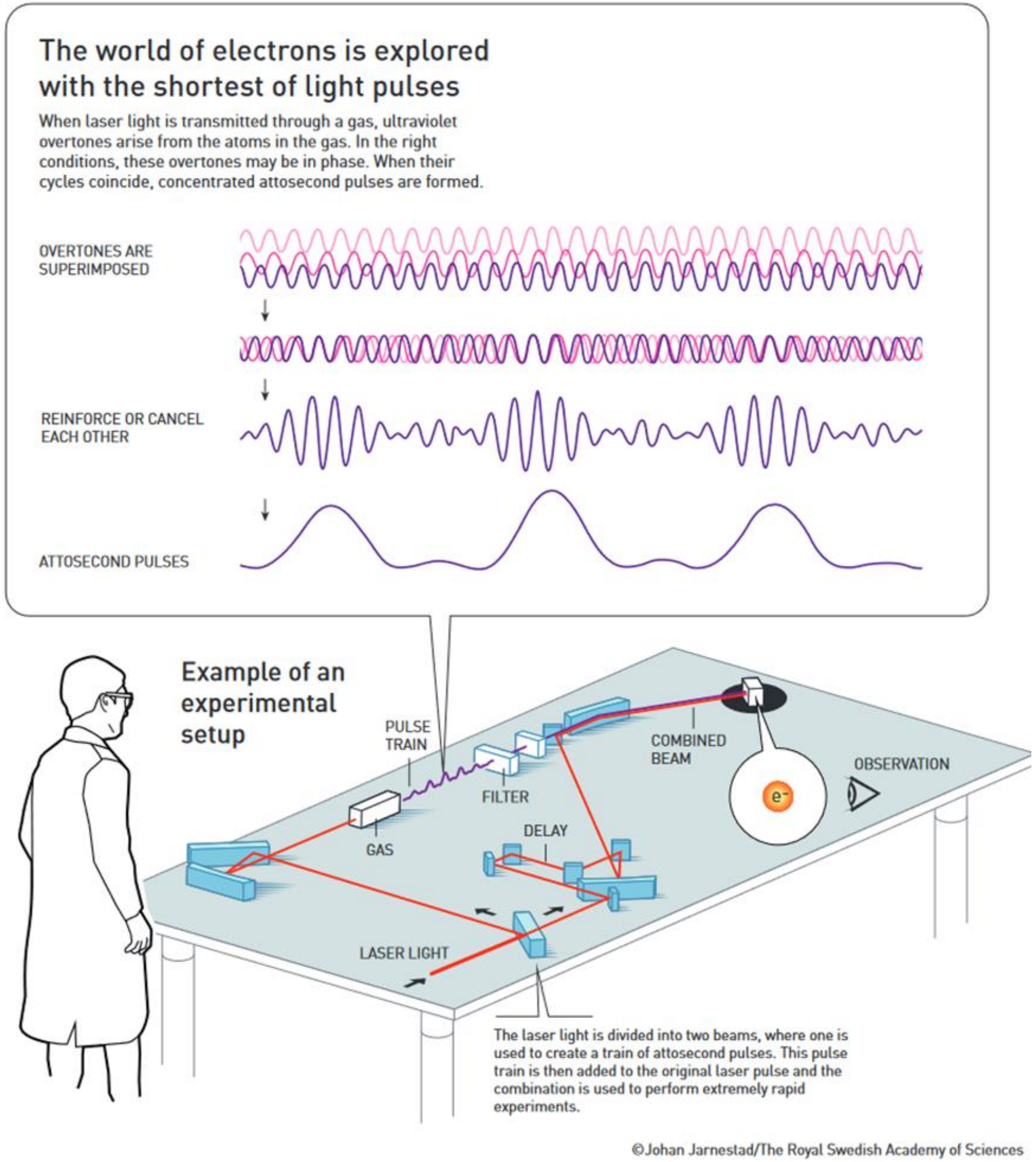
## XUV NIR pump-probe spectroscopy

APT: RABBIT (reconstruction of attosecond beating by interference of two-photon transitions)




IAP: FROG CRAB (complete reconstruction of attosecond bursts



# Pierre Agostini

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| 16,091 | 219 | 53 |
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| Citations by 10,202 documents | Documents | *h*-index View *h*-graph |

Characterization of Attosecond pulse trains in two-color fields: RABBIT (reconstruction of attosecond beating by interference of two-photon transitions)

## Top 5 highest cited papers

Article
Observation of a train of attosecond pulses from high harmonic generation — 2,263 Citations
Paul, P.M., Toma, E.S., Breger, P., ...Muller, H.G., Agostini, P.
***Science***, 2001, 292(5522), pp. 1689–1692
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Article • *Open access*
Observation of high-order harmonic generation in a bulk crystal — 1,206 Citations
Ghimire, S., Dichiara, A.D., Sistrunk, E., ...Dimauro, L.F., Reis, D.A.
***Nature Physics***, 2011, 7(2), pp. 138–141
Show abstract   View at Publisher   Related documents

Article
Free-free transitions following six-photon ionization of xenon atoms — 1,189 Citations
Agostini, P., Fabre, F., Mainfray, G., Petite, G., Rahman, N.K.
***Physical Review Letters***, 1979, 42(17), pp. 1127–1130
Show abstract   View at Publisher   Related documents

Article
Precision measurement of strong field double ionization of helium — 952 Citations
Walker, B., Sheehy, B., Dimauro, L.F., ...Schafer, K.J., Kulander, K.C.
***Physical Review Letters***, 1994, 73(9), pp. 1227–1230
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Review
The physics of attosecond light pulses — 783 Citations
Agostini, P., DiMauro, L.F.
***Reports on Progress in Physics***, 2004, 67(6), pp. 813–855
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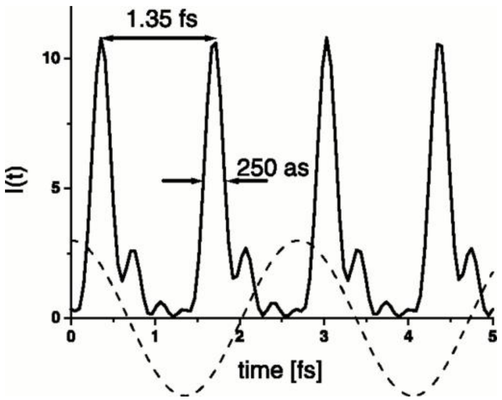
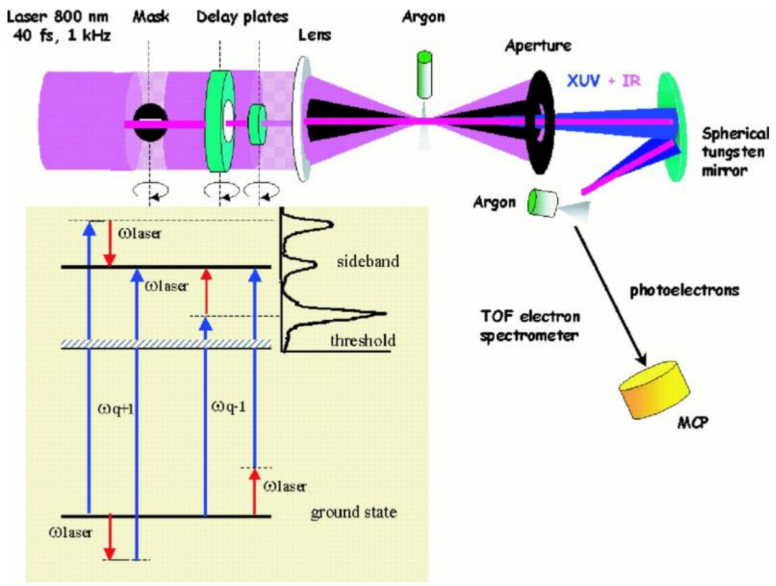
## Observation of a Train of Attosecond Pulses from High Harmonic Generation

P. M. PAUL, E. S. TOMA, P. BREGER, G. MULLOT, F. AUGÉ, PH. BALCOU, H. G. MULLER, AND P. AGOSTINI   Authors Info & Affiliations

**SCIENCE** • 1 Jun 2001 • Vol 292, Issue 5522 • pp. 1689-1692 • DOI: 10.1126/science.1059413



# Ferenc Krausz

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| 56,852 | 954 | 107 |
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| Citations by *26,270 documents* | Documents | *h*-index View *h*-graph |

## Top 5 highest cited papers

| | |
|---|---|
| Article • *Open access*<br>Attosecond physics<br>Krausz, F., Ivanov, M.<br>***Reviews of Modern Physics***, 2009, 81(1), pp. 163–234<br>Show abstract View at Publisher Related documents | 4,584<br>Citations |
| Article<br>Intense few-cycle laser fields: Frontiers of nonlinear optics<br>Brabec, T., Krausz, F.<br>***Reviews of Modern Physics***, 2000, 72(2), pp. 545–591<br>Show abstract View at Publisher Related documents | 2,887<br>Citations |
| Article<br>Attosecond metrology<br>Hentschel, M., Kienberger, R., Spielmann, Ch., ...Drescher, M., Krausz, F.<br>***Nature***, 2001, 414(6863), pp. 509–513<br>Show abstract View at Publisher Related documents | 2,593<br>Citations |
| Article<br>Attosecond science<br>Corkum, P.B., Krausz, F.<br>***Nature Physics***, 2007, 3(6), pp. 381–387<br>Show abstract View at Publisher Related documents | 1,820<br>Citations |
| Article<br>Attosecond control of electronic processes by intense light fields<br>Baltuška, A., Udem, Th., Uiberacker, M., ...Hänscht, T.W., Krausz, F.<br>***Nature***, 2003, 421(6923), pp. 611–615<br>Show abstract View at Publisher Related documents | 1,555<br>Citations |

Generation of few-cycle pulses for HHG, Generation of isolated attosecond pulses near the cutoff

Optics Letters Vol. 22, Issue 8, pp. 522-524 (1997) • https://doi.org/10.1364/OL.22.000522

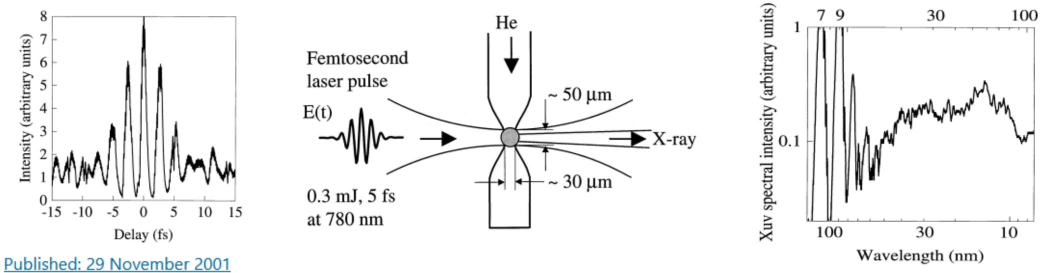
### Compression of high-energy laser pulses below 5 fs

M. Nisoli, S. De Silvestri, O. Svelto, R. Szipöcs, K. Ferencz, Ch. Spielmann, S. Sartania, and F. Krausz
Author Information Find other works by these authors

### Generation of Coherent X-rays in the Water Window Using 5-Femtosecond Laser Pulses

CH. SPIELMANN, N. H. BURNETT, S. SARTANIA, R. KOPPITSCH, M. SCHNÜRER, C. KAN, M. LENZNER, P. WOBRAUSCHEK, AND F. KRAUSZ Authors Info & Affiliations

SCIENCE • 24 Oct 1997 • Vol 278, Issue 5338 • pp. 661-664 • DOI: 10.1126/science.278.5338.661

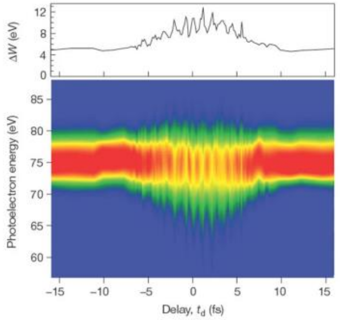


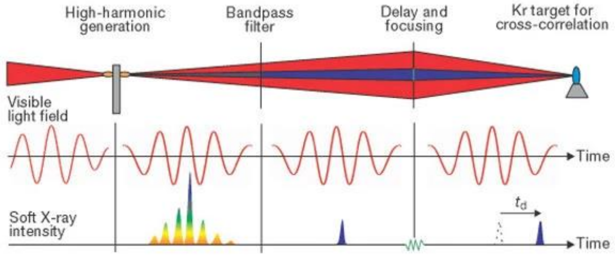

Published: 29 November 2001

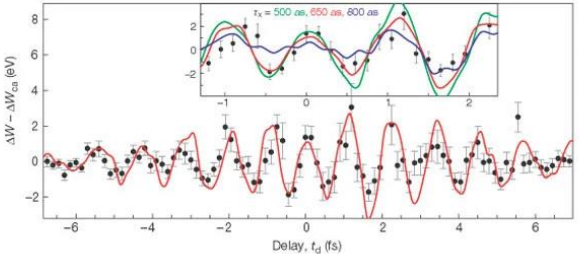
### Attosecond metrology

M. Hentschel, R. Kienberger, Ch. Spielmann, G. A. Reider, N. Milosevic, T. Brabec, P. Corkum, U. Heinzmann, M. Drescher & F. Krausz

*Nature* **414**, 509–513 (2001) | Cite this article



# Anne L‘Huillier

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| 21,229 | 370 | 67 |
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Discovery of HHG, TDSE model for strong field laser physics, ionization dynamics with attosecond pulses

## Top 5 highest cited papers

Article • *Open access*
Theory of high-harmonic generation by low-frequency laser fields — 3,556 Citations
Lewenstein, M., Balcou, Ph., Ivanov, M.Yu., L'Huillier, A., Corkum, P.B.
***Physical Review A***, 1994, 49(3), pp. 2117–2132
Show abstract | View at Publisher | Related documents

Article
Multiple-harmonic conversion of 1064 nm radiation in rare gases — 1,226 Citations
Ferray, M., L'Huillier, A., Li, X.F., ...Mainfray, G., Manus, C.
***Journal of Physics B: Atomic, Molecular and Optical Physics***, 1988, 21(3), 001
Show abstract | View at Publisher | Related documents

Article
High-order harmonic generation in rare gases with a 1-ps 1053-nm laser — 746 Citations
L'Huillier, A., Balcou, Ph.
***Physical Review Letters***, 1993, 70(6), pp. 774–777
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Article • *Open access*
Attosecond pulse trains using high–order harmonics — 637 Citations
Antoine, P., L'huillier, A., Lewenstein, M.
***Physical Review Letters***, 1996, 77(7), pp. 1234–1237
Show abstract | View at Publisher | Related documents

Article • *Open access*
Electron localization following attosecond molecular photoionization — 608 Citations
Sansone, G., Kelkensberg, F., Pérez-Torres, J.F., ...Martín, F., Vrakking, M.J.J.
***Nature***, 2010, 465(7299), pp. 763–766
Show abstract | View at Publisher | Related documents

### Multiple-harmonic conversion of 1064 nm radiation in rare gases

M Ferray[1], A L'Huillier[1], X F Li[1], L A Lompre[1], G Mainfray[1] and C Manus[1]
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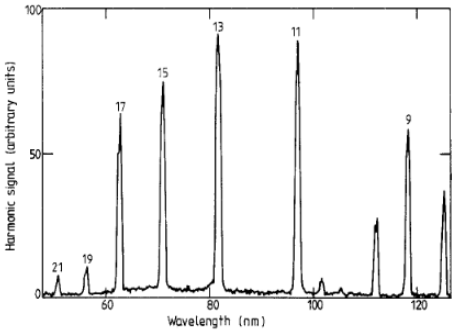
Journal of Physics B: Atomic, Molecular and Optical Physics, Volume 21, Number 3
**Citation** M Ferray *et al* 1988 *J. Phys. B: At. Mol. Opt. Phys.* **21** L31




### Theoretical aspects of intense field harmonic generation

A L'Huillier[1], K J Schafer[1] and K C Kulander[1]
Published under licence by IOP Publishing Ltd
Journal of Physics B: Atomic, Molecular and Optical Physics, Volume 24, Number 15
**Citation** A L'Huillier *et al* 1991 *J. Phys. B: At. Mol. Opt. Phys.* **24** 3315

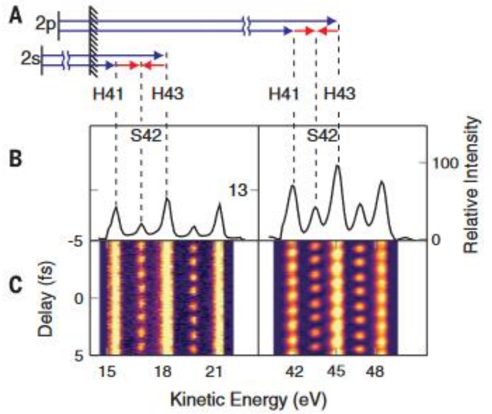
### Theory of high-harmonic generation by low-frequency laser fields

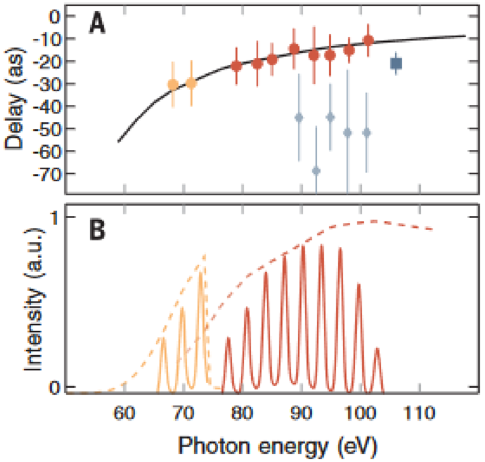
M. Lewenstein, Ph. Balcou, M. Yu. Ivanov, Anne L'Huillier, and P. B. Corkum
Phys. Rev. A **49**, 2117 – Published 1 March 1994

### Photoionization in the time and frequency domain

M. ISINGER, R. J. SQUIBB, D. BUSTO, S. ZHONG, A. HARTH, D. KROON, S. NANDI, C. L. ARNOLD, M. MIRANDA, J. M. DAHLSTRÖM, E. LINDROTH, R. FEIFEL, M. GISSELBRECHT, AND A. L'HUILLIER | fewer | Authors Info & Affiliations

SCIENCE • 2 Nov 2017 • Vol 358, Issue 6365 • pp. 893-896 • DOI: 10.1126/science.aao7043



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