The Nobel Prize in Physics 2023

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The Nobel Prize in Physics was awarded to Pierre Agostini of Ohio State University, Ferenc Krausz of the Max Planck Institute of Quantum Optics and the Ludwig-Maximilian University of Munich and Anne L'Huillier of the Lund University for „experimental methods that generate attosecond pulses of light for the study of electron dynamics in matter" The Prize acknowledges the tremendous experimental progress in the past 35 years that eventually enabled the investigation of the fastest electron transition processes in atoms, molecules and solids by using state-of-the-art femtosecond laser technology. As a result, a new field of research emerged and shortly after the establishment of the field of femtochemistry, attophysics came of age.

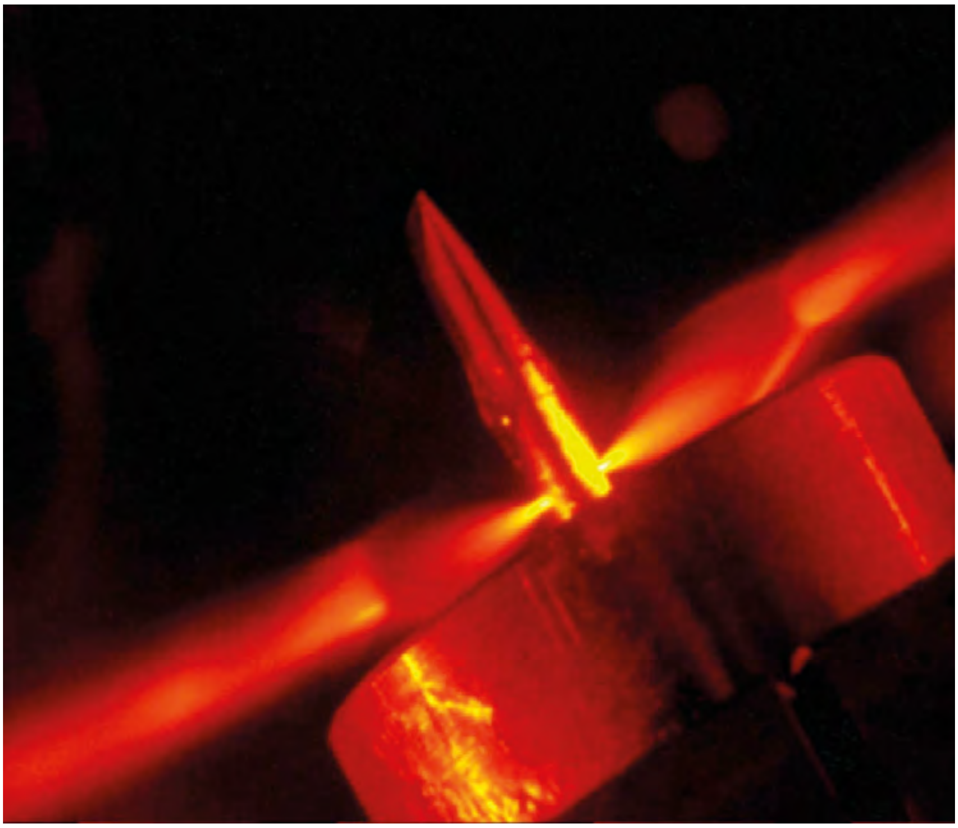
Progress in the generation of ultrashort laser pulses enabled fundamental research on light-matter interactions to enter a new realm. With tens of gigavolt per meter electric field strengths and pulse durations comprising only a few oscillation periods of light, extreme nonlinear phenomena could be explored – an ongoing era of strong-field physics full of surprises ensued.

Ultra-intense and ultrashort laser pulses have been at the core of this development.

Advanced laser Q-switching and mode-locking techniques enabled continuous rapid growth of the electric field strength of ultrashort laser pulses already in the 1970s. An early example of the new type of bewildering experimental observations is the discovery of above threshold ionization by Pierre Agostini and his colleagues in 1979. Focussing intense ultrafast laser pulses into a cloud of Xe atoms placed inside a photoelectron spectrometer, they observed that the laser is not only capable of ionizing the atoms. Remarkably, they demonstrated that the electrons can absorb several more photons of 1.2 electronvolt (eV) energy than the absolute minimum of 11 required to overcome the ionization potential of 12.3 eV.

Subsequently, considerable research effort was invested in experiments about laser-matter interaction studies and strong-field physics emerged as a substantive field of research comprising experimental and theoretical research teams inspecting the beauty of nonlinear light-matter interaction phenomena. The year 1988 marked an important milestone when under comparable strong-field conditions Anne L'Huillier and her colleagues observed the generation of high-order harmonic radiation of laser light. In their experiment, intense laser pulses emitted by an Nd-doped YAG laser interacted with Ar atoms. This led to the emission of radiation up to the 33rd harmonic of the fundamental frequency, just shy of 40 eV photon energy. This high photon energy and peculiarities of the emitted spectrum including the counterintuitive similarity of the amplitudes of individual harmonics suggested a connection to the findings of Agostini and colleagues. However, a clear quantum mechanical

▾ Attosecond light source driven by ultrashort laser pulses. Ne atoms used for HHG stream into a vacuum chamber and emit (invisible) attosecond pulses that co-propagate with the laser light. (credit: attoworld.de)

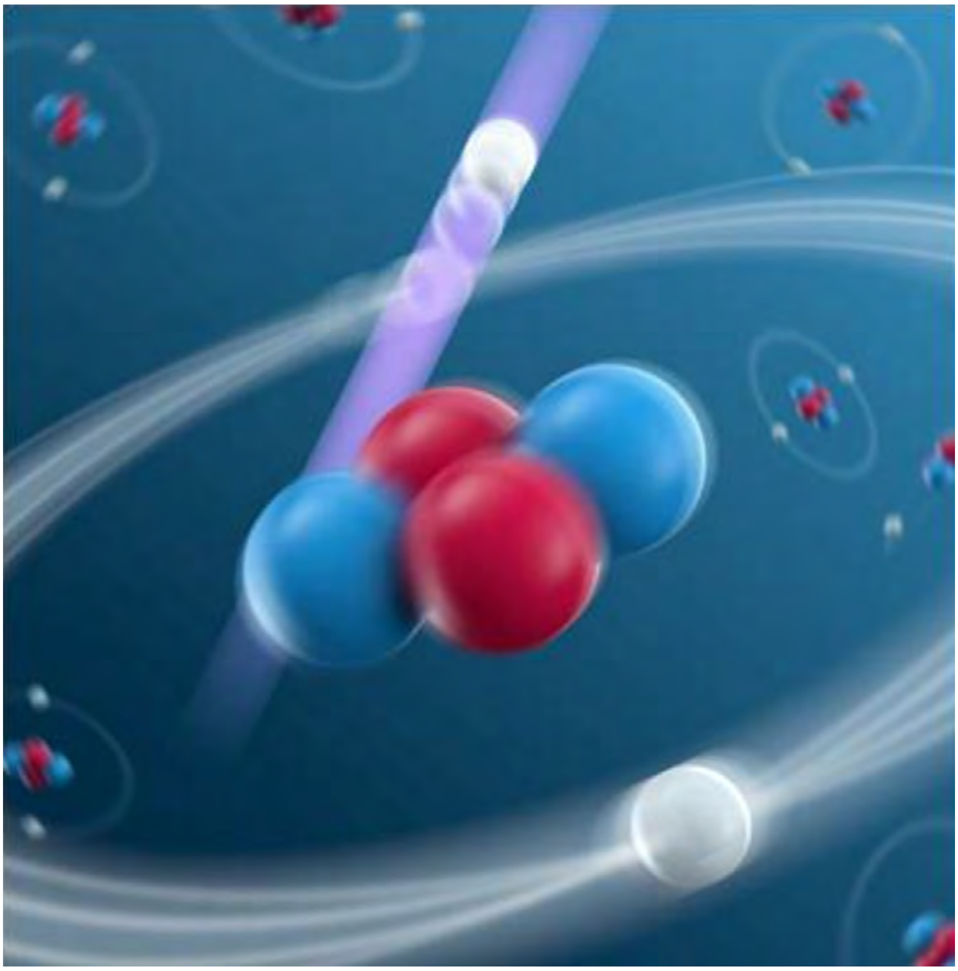


picture of the involved processes was pending at that time.

In the 1990s, much discussion was devoted to the mechanism of the high-order harmonic generation (HHG) process and to whether the emitted high-frequency light was coherent and the observed spectral features could correspond to attosecond pulses in the time domain. However, at that time experimental tools to investigate the radiation were limited to extreme ultraviolet grating spectrometers, incapable of sampling the temporal evolution of the emitted UV light and leaving unclear if the spectral phase of the high harmonic radiation would allow to form short pulses.

While it had been recognised that the spectral bandwidth of the emitted radiation in principle would support pulses of attosecond duration, for a time domain characterisation fundamentally new experimental tools had to be developed. An experimental long-distance race resulted in two experiments demonstrating the feasibility to generate attosecond duration bursts of light via the HHG process. In Vienna, Ferenc Krausz and his team developed a time-domain sampling technique in which co-propagating high-harmonic XUV and near-infrared laser pulses photoionised Ar atoms. The team detected the kinetic energy of the emitted photoelectrons and found it to be modulated by the presence of the near-infrared laser in a way that proved beyond doubt that a single 650-attosecond duration pulse (isolated in time) had caused the photoionisation. At the same time, Pierre Agostini and his colleagues employed a novel frequency-domain technique enabling access to the spectral phase information of the XUV radiation and verified the existence of a train of 250-attosecond pulses in their experiment.

Advancing time-domain and frequency-domain attosecond techniques formed a toolbox capable of scrutinising quantum mechanical processes on their natural time-scale. Suddenly, the treatment of electronic transitions as virtually instantaneous became a too simplistic model. Fundamental discoveries include the observation and control of electronic wavepacket motion in matter, recording the time photoemission and photoexcitation take and inquisitions on the time domain implications of quantum tunnelling.



▲ How long does it take a Helium atom to notice it got photo-ionized? Attosecond measurements have sparked the development of high-level quantum theories that include multi-electron correlations and boosted the understanding of transient states of matter. (credit: A. Gelin)

The quick progress in fundamental research triggered by attosecond science also fostered a tremendous advance in femtosecond laser technology in the past 30 years. Laser systems used for this research were developed based on the chirped pulse amplification principle (see the work of Gérard Mourou and Donna Strickland, Nobel Laureates in Physics in 2018) and ultrashort, amplified laser pulses are now available that contain only one oscillation cycle of the electromagnetic wave. Next to advances in ultrafast opto-electronic and magneto-optical technology, novel laser sources are nowadays employed in biomedical analysis techniques that will permit early-stage cancer and cardiovascular disease detection in human blood serum. These developments, in the spirit of the Nobel prize dedication, evidence how the continuous interaction between fundamental physics research and the application of state-of-the-art lasers continue to serve "for the greatest benefit to humankind". ■

■ **Peter Dombi,**
Wigner Research Centre for Physics, Budapest, Hungary
■ **Martin Schultze,**
Graz University of Technology, Institute of Experimental Physics, Austria

(both authors completed their PhD under the supervision of Ferenc Krausz)