time is defined by physical processes

modified from LCLS/SLAC website
a history of ultra-fast: breaking the fs barrier

10 ps
Nd:glass
Dye
S-P Dye
1 ps
Diode
Nd:YAG

100 fs
CW Dye
CPM Dye
Color Center

10 fs
DYE LASER BREAKTHROUGHS

1 fs
first laser

“new” era: attophysics

atomic unit of time ≡ 24 as

Vienna

Saclay

femtosecond barrier

10 as


CPA

Cr:LiS(C)AF
Er:fiber
Nd:YLF

Nd:YAG

w/Compression

Ti:sapphire

Cr:YAG

Cr:forsterite

Nd:YAG

Nd:glass

Nd:YLF

Ti:sapphire

Nd:YAG
challenges of breaking the fs barrier

• sub-femtosecond \(\Rightarrow\) short wavelengths (XUV, x-rays)
  single-cycle 25 as pulse \(\Rightarrow\) 7.5 nm (\(\sim\)165 eV photon energy)

• uncertainty principle: \(\Delta \nu \Delta t \cong 1\) \(\Rightarrow\) need bandwidth!!
  single-cycle 25 as pulse \(\Rightarrow\) \(20 \times 10^{15}\) Hz frequency spread

• control the phases of the field, i.e. mode-locking

• attosecond metrology
the growth of attosecond science

- attosecond science can address a broad range of interdisciplinary problems specifically, electron correlation and strongly damped systems

from ISI Web of Knowledge
attosecond production approaches

- coherent or cascade stimulated Raman scattering
  Kaplan, Harris, Sokolov....

- solid target interactions, non-relativistic/relativistic
  Kaplan, Mourou, Naumova....

- 4th generation light sources: XFELs & ERLs

- high harmonic generation from gases
  Farkas, Toth, L’Huillier....
Nonlinear frequency conversion: $\omega_q = q\omega_{800}$

- Intense laser-atom interaction produces a comb of odd harmonic
- Harmonics result from the physics of a field-driven electron
- Attosecond pulses are formed by Fourier synthesis
- Physics needs Schrödinger’s and Maxwell’s equations
- HHG sources are table-top

Saclay, Chicago, 1987
attosecond beamline and end-station

attosecond pulse train + reference field

selection in argon: harmonic order 13 to 31

intense ultra-fast laser 0.8-2 μm

toroidal focusing mirror

electron\ion spectrometer

argon jet

reference fundamental field

beam splitter

delay

Al filter

aperture

generation

frequency time

NAS 2011 April 5
attosecond laboratories are developing world-wide
US (4), Europe (13), Canada (1), Japan (2), Korea (1)
state-of-the-art attosecond generation

- attosecond pulse train
  - dispersion compensation (Lund group)
    - 130 as, 35 eV
  - long-wavelength fundamental field (Ohio group)
    - 120 as, 200 eV

- isolated attosecond pulse
  - polarization gate, dispersion compensation, CEP
    - 130 as, 35 eV, 0.5 nJ (Milano group)
  - 1.4-cycle driver, dispersion compensation
    - 80 as, 120 eV, 0.5 nJ (MPQ-Garching group)
MPQ atto-streaking for time-resolving Auger decay

detected electron energy (classical result):
\[ W_f = W_i + 2U_p \sin(\omega_f t)^2 \cos 2\theta + [8W_i U_p]^{1/2} \sin(\omega_f t) \cos \theta \]

from Drescher et al., Nature 419, 803 (2002)
• the 90 eV attosecond pulse excites a core electron (3d) in Kr
• the ir-field streaks the energy of the photoelectron & Auger
• energy streak is proportional to the phase (time)

\[ \tau_A = 7.9 \pm 0.9 \text{ fs} \]
precision in a time-domain electron interferometer

Mach-Zehnder interferometer
- key elements: 2 beam splitters (BS)
- sensitive measurement of phase shifts
- precision through fringe counting

Material

theory: Ken Schafer

from Mauritsson et al. PRL 105, 053001 (2010)
fundamental questions for attosecond science

electronic response at early times

• universal attosecond response
  Breidbach & Cederbaum, PRL 94, 033901 (2005)

• evolution of electron correlation
  Burgdorfer et al., PRL 103, 063002 (2009)
  2-photon double ionization of helium

these issues are uniquely addressed by attosecond science