FAZST-Femto-Atto-ZeptoSecond
Science & Technology

Andre D Bandrauk, FRSC, FAAAS
Canada Research Chair
Computational Chemistry & Molecular Photonics
Universite de Sherbrooke
http://pages.usherbrooke.ca/adbandrauk
“Molecules in Intense Laser Fields – Femto to Atto to ZeptoSecond Dynamics”

and / or

“FAZSST-Femto-Atto-ZeptoSecond Science & Technology”

André D, Bandrauk, PhD, FRSC, FAAAS
Canada Research Chair
Computational Chemistry & Molecular Photonics
Université de Sherbrooke
Potential energy: \( V_o = \frac{e^2}{a_o} = 1 \) Hartree = 27.2 eV.  

Electric field \( E_o = \frac{e}{a_o^2} = 5 \times 10^9 \) V/cm.

Intensity \( I_o = cE_o^2 / 8\pi = 3.5 \times 10^{16} \) W/cm\(^2\).

Distance \( a_o = 0.0529 \) nm.

Time: \( t(a_o)=24 \) as, \( 2\pi t_o=152 \) as, \( t(mc^2)=1.3 \) zeptos

### Table I

<table>
<thead>
<tr>
<th>Time (s)</th>
<th>Intensity (Watts/cm(^2))</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nano 10^{-9}</td>
<td>Giga ( 10^{12} )</td>
<td>1980</td>
</tr>
<tr>
<td>Pico 10^{-12}</td>
<td>Tera ( 10^{12} )</td>
<td>1985</td>
</tr>
<tr>
<td>Femto 10^{-15}</td>
<td>Peta ( 10^{15} )</td>
<td>1990</td>
</tr>
</tbody>
</table>

\( 1 \) a.u. = \( 24 \times 10^{-18} \)  

\( I_o = 3.5 \times 10^{16} \) W/cm\(^2\)

\( 10^{\infty} \) - Schwinger Limit

The intensities discussed in the present article, \( 10^{14} \geq I \geq 10^{16} \) W/cm\(^2\) correspond to fields approaching the internal Coulomb potentials of atoms and molecules (\( V_o \), equations (1-3)), thus inducing considerable distortions of intermolecular potentials. In the dressed state representation these radiatively induced distortions creating LIMP’s as discussed above lead to bond softening via laser-induced avoided crossing of molecular potentials [26-27]. At such intensities, one needs to consider further ionization and the remaining molecular ion potentials become LIMP’s in the presence of intense laser pulses. The molecular ions, bound or dissociative can also undergo Above-Threshold Dissociation, ATD, [20], [26-27].

Schwinger limit \( \sim 10^{29} \) W/cm\(^2\)

Sunlight: 0.12 W/cm\(^2\)
structure and dynamics in the microcosm

- electrons in nanostructures
- atoms in molecules & solids

Electrons in nanostructures:
- $\Delta W_{\text{electronic}} \sim \text{sub-eV}$
- $\Delta W_{\text{valence}} \gg 1\text{eV}$

Atoms in molecules & solids:
- $\Delta W_{\text{vibr}} \sim \text{milli-eV}$

Nuclear structure & dynamics:
- $\Delta W_{\text{core}} \gg 10\text{eV}$

Microscopy, diffraction:
- $10^{-9}$
- $10^{-12}$

Time [s]:
- $10^{-18}$
- $10^{-15}$
- $10^{-12}$

Attosecond spectroscopy
F Krausz, MPQ, MUenchen
The electric field $E(t)$ is given by $E(t) = \varepsilon_0(t) \cos(\omega t + \Phi)$. For $\lambda = 800$ nm, 1 cycle = 2.66 fs. 

Experimental asymmetries (Garching).
F. Lindner, Ph.D. Thesis.
$\lambda=760 \text{ nm}$, $\tau_p=5 \text{ fs}$.

Theory: $\tau_p=5 \text{ fs}$,
$I=3.1 \times 10^{13} \text{ W/cm}^2$
$\lambda=800 \text{ nm}$
$\theta < 15^\circ$

$I=4.8 \times 10^{13} \text{ W/cm}^2$ (exp.)

Exciting electrons

Chemistry rarely grabs the limelight. But in 2011 it will try to
Les lasers traquent les mouvements des électrons

Siegfried Bauer, Max Planck Institut für Quantenoptik, Garching, Allemagne.

Pour le premier prix Nobel de physique 2010, qui a récompensé l'atteinte de la méta-stabilité des atomes par les lasers, le chercheur Siegfried Bauer, de l'Institut Max Planck pour la quantiqueoptique, a créé un miroir atomique à précession. Les lasers peuvent alors les faire vibrer dans des mouvements précis, ce qui a permis de mesurer la position des atomes avec une précision sans précédent. Cette avancée technique a ouvert de nouvelles perspectives dans la compréhension de la matière et dans la technologie de l'information.

Une moisson de prix

Siegfried Bauer est également le président de l'Institut Max Planck pour la quantiqueoptique, qui a reçu le prix Nobel de physique 2010 pour ses travaux sur la méta-stabilité des atomes. Le prix Nobel est attribué chaque année par la Commission Internationale de la Science, et est destiné à reconnaître les contributions les plus remarquables dans le domaine de la physique. Le prix Nobel de physique 2010 est attribué à Siegfried Bauer pour ses travaux sur la méta-stabilité des atomes, qui ont ouvert de nouvelles perspectives dans la compréhension de la matière et dans la technologie de l'information.

Les lasers traquent les mouvements des électrons

Siegfried Bauer, Max Planck Institut für Quantenoptik, Garching, Allemagne.

Pour le premier prix Nobel de physique 2010, qui a récompensé l'atteinte de la méta-stabilité des atomes par les lasers, le chercheur Siegfried Bauer, de l'Institut Max Planck pour la quantiqueoptique, a créé un miroir atomique à précession. Les lasers peuvent alors les faire vibrer dans des mouvements précis, ce qui a permis de mesurer la position des atomes avec une précision sans précédent. Cette avancée technique a ouvert de nouvelles perspectives dans la compréhension de la matière et dans la technologie de l'information.

Une moisson de prix

Siegfried Bauer est également le président de l'Institut Max Planck pour la quantiqueoptique, qui a reçu le prix Nobel de physique 2010 pour ses travaux sur la méta-stabilité des atomes. Le prix Nobel est attribué chaque année par la Commission Internationale de la Science, et est destiné à reconnaître les contributions les plus remarquables dans le domaine de la physique. Le prix Nobel de physique 2010 est attribué à Siegfried Bauer pour ses travaux sur la méta-stabilité des atomes, qui ont ouvert de nouvelles perspectives dans la compréhension de la matière et dans la technologie de l'information.
MAXWELL – SCHROEDINGER

MAXWELL

\[
\frac{\partial^2 E}{\partial z^2} - \frac{1}{c^2} \frac{\partial^2 E}{\partial t^2} = \frac{4\pi}{c^2} \frac{\partial^2 P}{\partial t^2}
\]

\[P = \text{Medium Polarization} = P(E)\]

(1st Order \(P = \alpha E\))

SCHROEDINGER

\[
i\hbar \frac{\partial |\psi\rangle}{\partial t} = (\hat{H}_0 + \hat{V}(t))|\psi\rangle
\]

\[P = P(E) = n_0 \langle \psi | \hat{\mu}_0 | \psi \rangle\]

\[|\psi\rangle = \sum_j c_j e^{iE_j t/h} |\Psi_j\rangle\]

\[V_{ii} = -P_{ii} \left(e(z,t)\cos(kz-\omega t)\right)\]


**Figure 1.** (a) Atomic electronic potentials distorted respectively by the presence of a strong positive, null, and negative external electric field. (b) Electronic molecular potentials in a positive electric field, as a function of the internuclear distance $R$. The Stark shift $\Delta \epsilon_{ij}$ between the two localized molecular orbitals $\epsilon_i$ and $\epsilon_j \approx E_{\text{int}}R$. 
Recollision physics
Paul B. Corkum

A technique that uses light to create particle collisions that create light is poised to provide unprecedented access to the inner workings of atoms and molecules.

In 1996, Ernest Rutherford discovered that a particle can pass through a metal film. This experiment, which helped Rutherford identify the atomic nucleus, was a dramatic demonstration that collisions between particles could tell us about the structure of matter. Nearly a century later, high-energy collisions between subatomic particles have revealed the fundamental building blocks of our world—quarks, mesons, and so on—and low-energy collisions have been central to understanding and harnessing nuclear physics.

Just over 50 years after Rutherford's experiment, the laser was demonstrated. Since then, optical physics, which deals with interactions between light and matter, has developed powerful methods for exciting, probing, and controlling matter and its dynamics. The precision of optical experiments has reached the point where some of the most fundamental questions of particle physics can be studied faster optically than by collisions.

Although optical and collision physics are traditionally considered separate disciplines sharing little, if any, overlap, the emerging field of recollision physics unites the two. In a recollision, the oscillating field of a laser pulse causes an electron to accelerate away from an atom or molecule and then, upon reversal of the field, re-collide with its parent ion. Whereas traditional collision physics relies on large accelerators and magnets to arrange the collision, in recollision physics it is the laser field that provides the deceleration and the atom/ion that provides the electron with speeds it is probed. Through recollision, optics gains access to the well-developed capability to probe the structure of matter via collisions (the focus of this article) and collision physics gains access to the capability to study, probe, and control matter with light.

**Two coherence transfers**

Consider a molecule illuminated by a pulse of coherent IR light. If the light is intense enough, roughly 10¹⁴ W/cm² or higher (see box 1), then at each end of the oscillating electromagnetic field, the valence-electron wavefunction will partially lose its so-called tunnel intensity. Strictly speaking, tunneling is a DC phenomenon. However, Levick Keizer showed nearly half a century ago that multiphoton ionization can approximate tunneling in a time and scale when IR light is used. Thus, I will speak of laser tunneling or simply tunneling, throughout the paper. Through tunneling, the coherent light pulse splits the electron wavefunction into two mutually coherent parts—the bound-state wavefunction and the tunnel-assisted wavepacket. (See figure 1.)

Once the electron has tunnelled, the resulting wavepacket—now in the continuum, freed from the pull of its parent ion—evolves in a semiclassical manner by the laser field. The classical approximation of subcycle electron motion has a long history in plasma physics. It is useful when many photons are involved.

What happens next depends on the polarization of the light pulse. If the polarization is circular, then no component of the wavefunction emerges from the atom or molecule.
ADB, S. Barmaki, G. Kamta

KJ Yuan, ADB
PRA 80, 053404 (2009)
\[ \Delta t = \frac{2}{3} \tau = 1.8 \text{ fs} \]
\[
V(z,\rho) = -\frac{e^2}{\sqrt{z^2 + \rho^2}}
\]

Le potentielle (eV)

\[
\phi = 0
\]

blue electrons will return

\[
\frac{I}{I_{at}} = \frac{3.51 \times 10^{16}}{W/cm^2}.
\]

(Vo > 0)

Semi-classical model, by P. Corkum  
(Vo = 0) (1993).

\[
n_{cut} = \left[ I_p + 3.17 U_p \right] / \omega_L, \quad U_p = \frac{I}{4 \omega_L^2},
\]

Cuttof at:

I_{at} = 3.51 \times 10^{16} \text{ W/cm}^2.
$|\alpha(\omega)|^2$ [arb. units]

Harmonic order

Fs + asec pulses

Single fs pulse

20nm

6x10$^{13}$ W/cm$^2$

20nm
Step 1: get spectrum

\[ a(t) = \langle \psi(t) | -\delta H / \delta r | \psi(t) \rangle \]

\[ a(\omega) = \frac{1}{2\pi} \int_{-\infty}^{\infty} a(t) e^{-i\omega t} dt \]

Step 2: select frequency region between \( \omega_1 < \omega < \omega_2 \)

Step 3: come back to time domain

\[ \tilde{a}(t) = \int_{\omega_1}^{\omega_2} a(\omega) e^{i\omega t} d\omega \]

\[ \Delta \omega = \omega_2 - \omega_1 \]

\[ \tau = \frac{1}{\Delta \omega} \rightarrow \text{attosecond} \]

= 3 Angstroms(10^{-8}cm) / c(3 \times 10^{10}cm/s-1)
Coupling of macroscopic Maxwell’s equations with many TDSE’s.


\[
\begin{align*}
\partial_t B(r, t) &= -\nabla \times E(r, t) \\
\partial_t E(r, t) &= \nabla \times B(r, t) - 4\pi \partial_t P(r, t) \\
\nabla \cdot B(r, t) &= 0 \\
\nabla \cdot (E(r, t) + P(r, t)) &= 0
\end{align*}
\]

\[
P(r, t) = n(r) \sum_{i=1}^{m} P_i(r, t) = \sum_{i=1}^{m} \chi \Omega_i(r) \int_{\mathbb{R}^3} \psi_i r' \psi_i^* \\
i \partial_t \psi_i(r', t) &= -\frac{\Delta r'}{2} \psi_i + r' \cdot E_i \psi_i + V_c \psi_i, \\
&\quad \forall i \in \{1, \ldots, m\}
\]
The numerical model is the one presented in [19], where the gas domain is divided in small cells of gas denoted by $\Delta v$ (corresponding the $\Omega_i$'s of Section 2) and in which we solve 1 TDSE, representing the $n\Delta v$ molecules of the cell. In practice 3d Maxwell’s equations are solved in parallel with $\sim 140,000$ 1d TDSE’s, see Fig. 5 and [17]. We then represent at

Figure 5: Numerical geometry
Improvement of the model I - microscopic approach

Another approach is presented in Lorin, Bandrauk, Chelkowski, Num. Methods for Partial Diff. Eq., (2008). A method to transmit free electron from a molecule to another. Based on a particular choice of boundary conditions (Volkov)

Figure: Free electron transmission
Results I - $I \sim 2 \times 10^{16} \text{W} \cdot \text{cm}^{-2}$, $n_0 \sim 3 \times 10^{20} \text{mol} \cdot \text{cm}^{-3}$

Figure: $|E_y|^2$ - 4.5 μm after the waist in vacuum and gas
Two (minimum) or one (maximum) attosecond pulses
Frequency-up conversion, 1st --> 3rd harmonics

ADB et al, J Molec Str. 735, 203 (2004)
Goulielmakis, Krausz (2009-2010)
Yedder, LeBris, Chelkowski, Bandrauk, PRA 69, 041802 (2004)

((Bartels.Murnane.Rabitz.PRA 70.043404(2004))
Effect of Nuclear Motion on Molecular High-order Harmonics and on Generation of Attosecond Pulses in Intense Laser Pulses

André D. Bandrauk, Szczepan Chelkowski, Shinnosuke Kawai, and Huizhong Lu

Département de Chimie, Université de Sherbrooke, Sherbrooke, QC, J1K 2R1 Canada

Abstract

We calculate harmonic spectra and shapes of attosecond pulse trains using numerical solutions of Non-Born Oppenheimer time-dependent Shrödinger equation for 1-D H₂ molecules in an intense laser pulse. A very strong signature of nuclear motion is seen in the time profiles of high order harmonics. In general the nuclear motion shortens the part of the attosecond pulse train originating from the first electron contribution but it may enhance the second electron contribution for longer pulses. The shape of time profiles of harmonics can thus be used for monitoring the nuclear motion.

PACS numbers: 42.65.Ky, 42.65.Re, 42.60.Hz, 32.80.Rm

Phys Rev Lett( 2008,)101,153901
J Phys B 42,075602 (2009)
La dynamique de 4-particules: p+p+e−+e− décrite par l’éq. de Schrödinger solutionnée numériquement

Équation de Schrödinger dependant de temps pour une molecule H₂ exposée au champ laser intense décrit par : E(t)=ε(t) cos(ωₜₜ)

(polarisation linéaire)

\[ a.u. \ e = \hbar = m_e = 1 \]

\[
\frac{i}{\hbar} \frac{\partial \psi(z_1, z_2, R, t)}{\partial t} = [H_e + H_N + V(z_1, z_2, t)] \psi(z_1, z_2, R, t), \quad (1)
\]

\[
H_e = \sum_{i=1}^{2} \left[ -\frac{1}{2} \frac{\partial^2}{\partial z_i^2} - \frac{1}{[(z_i + R/2)^2 + c]^{1/2}} - \frac{1}{[(z_i - R/2)^2 + c]^{1/2}} \right] + V_{\text{rep}}(z_1, z_2) \quad (2)
\]

\[
V_{\text{rep}}(z_1, z_2) = \frac{1}{[(z_1 - z_2)^2 + d]^{1/2}}; \quad H_N = -\frac{1}{2M} \frac{\partial^2}{\partial R^2} + \frac{1}{R} \quad (3)
\]

\[
V(z_1, z_2, t) = (z_1 + z_2)\varepsilon(t) \cos(\omega_L t) \quad (4)
\]

\[
d(t) = \langle z_1 + z_2 \rangle = \int_{-\infty}^{\infty} dz_1 \int_{-\infty}^{\infty} dz_2 \int dR \ \psi^*(t) (z_1 + z_2) \psi(t)
\]
Analyse en temps-frequence de Gabor (ondelettes):

\[ d_G(t, \omega) = \int_{-\infty}^{\infty} dt' G(t,t') \exp(-i \omega t) \, d(t) \]

\[ G(t-t') = \exp\left[-\frac{(t-t')^2}{2\sigma_0^2}\right], \quad \sigma_0 = 0.1 \text{ fs} \]

\[ d_G(t, \omega) = \text{cte} \int_{-\infty}^{\infty} d\omega' \, e^{-b(\omega-\omega')^2} \, e^{i\omega't} \, d_F(\omega') \]

\[ |d_G(t,\omega)| \text{- profile temporaire des impulsions atto dans un train, } \Delta \omega \sim 5-10 \omega_L \]

Temps (périodes du laser \( T_{\text{las}} \)), \( T_{\text{las}} = 2.67 \text{ fs} \)

\( T_{\text{v}(H_2)} \sim 7 \text{ fs} \)
\[ V = \frac{1}{R} - \sum_{j=1}^{2} \frac{1}{\sqrt{(z_j - R/2)^2 + a}} + \frac{1}{\sqrt{(z_j + R/2)^2 + a}} \]

\[ a_{el} = \frac{d^2}{dt^2} z(t) = -2E(t) - \left< \frac{\partial V}{\partial z_1} + \frac{\partial V}{\partial z_2} \right> = -2E(t) - \left< F_+ + F_- \right> \]

\[ \mu a_R = \mu \frac{d^2}{dt^2} R(t) = -\left< \frac{1}{R^2} \right> - \left< \frac{\partial V}{\partial R} \right> = -\left< \frac{1}{R^2} \right> - \frac{1}{2} \left< F_+ - F_- \right> \]

where

\[ F_\pm = \sum_{j=1}^{2} \frac{z_j \pm R/2}{[(z_j \pm R/2)^2 + a]^{3/2}} \]

Thus, very similar expressions determine electron and proton acceleration. For electrons:

\[ F_+ + F_- = f_{el}(z_1, z_2) \]

is an odd function with respect to the inversion

\[ z_1 \rightarrow -z_1, \ z_2 \rightarrow -z_2 \]

leading to odd harmonics, whereas for protons

\[ F_+ - F_- = f_{prot}(z_1, z_2) \]

is an even function with respect to the inversion

\[ z_1 \rightarrow -z_1, \ z_2 \rightarrow -z_2 \]

leading to even harmonics.
$\lambda = 800 \text{ nm}$
The figure shows the electric field profile over time with cycles indicated. The time profile of \( z \) (a.u.) and \( R \) (a.u.) are depicted for the 40th harmonic of \( H_2 \) with \( I = 4 \times 10^{14} \text{ W/cm}^2 \). The wavelengths are given as \( \lambda = 800 \text{ nm} \).
Measuring electron wave packets

1. Attosecond pulses are fast enough to observe electron wave packets.

2. Electron wave packets are resolved through changes to the photo-electron spectrum as a function of pump-probe time delay.

3. The attosecond pulse projects the momentum distribution into the continuum.

Yudin et al, Phys Rev A 72, 51401(R) (2005)

“Observing Electron Motion in Molecules”
FIG. 53. (Color) Proposal for inducing attosecond electron wave-packet dynamics by a 0.8-fs, 115-nm VUV pump pulse in H$_2^+$ and probing it with a time-delayed 0.1-fs, 20-nm XUV pulse (Bandrauk et al., 2004). Both pulses are polarized parallel to the molecular axis. (a) Contour plot of the electron probability distribution along the molecular axis for an internuclear distance of eight atomic units vs pump-probe delay. (b) Asymmetry factor $(P_+ - P_-)/(P_+ + P_-)$ vs delay, where $P_+$ and $P_-$ represent the probability of observing the electron liberated by the XUV probe in the positive or negative direction (along the molecular axis), respectively. Adapted from Bandrauk et al., 2004.

FIG. 54. (Color) Computed ultrafast positive charge (hole) migration in a tryptophane-terminated tetrapeptide (Remacle and Levine, 2006a, 2007). (a) The hole density shown in red indicates that the charge swings across the entire peptide from the aromatic amino acid on the left to the N end on the right within less than one femtosecond, following excitation of the electronic wave packet on an attosecond time scale. This hyperfast charge migration is proposed to be probed by measuring the kinetic energy distribution of photoelectrons released by a time-delayed sub-fs XUV pulse. (b) A series of such freeze-frame spectra calculated for a 250-as, 95-eV probe pulse at different pump-probe delays. From Remacle and Levine.
Circular polarization Excitation at 800 nm  \( I=10^{14} \text{ W/cm}^2 \)

Electron Whirlpool – Tourbillon Electronique – Elektronischer Wirbel (J Manz- FU Berlin)
II. THEORETICAL MODELS

In linearly polarized recollision with parent ions, maximum harmonic energies are given from the initial zero velocity ionization model by \( E_p = \frac{3.17 U_p}{10^3} \) [3–6], whereas collision with neighboring ions gives harmonic energies up to \( E_d + 8U_p \) [9–12]. For circularly polarized laser pulses of maximum amplitude \( E_0 \), corresponding to intensity \( I_0 = 77E_0^2/2 \) and frequency \( \omega_0 \),

\[
E_x(t) = E_0 \cos(\omega_0 t + \phi), \quad E_y(t) = E_0 \cos(\omega_0 t + \phi),
\]

the classical field equations of motion \( \dot{x}(t) = -E_x(t), \dot{y}(t) = -E_y(t) \) give the laser-induced velocities [we use atomic units (a.u.) \( \epsilon = \hbar = m_e = 1 \) throughout]

\[
\dot{x}(t) = -\frac{E_0}{\omega_0} [\sin(\omega_0 t + \phi) - \sin \phi],
\]

\[
\dot{y}(t) = -\frac{E_0}{\omega_0} [\cos(\omega_0 t + \phi) - \cos \phi],
\]

with initial velocity conditions \( x(0) = y(0) = 0 \), and displacements,

\[
x(t) = \frac{E_0}{\omega_0} [\cos \phi - \cos(\omega_0 t + \phi) - \omega_0 t \sin \phi],
\]

\[
y(t) = -\frac{E_0}{\omega_0} [\omega_0 t \cos \phi + \sin \phi - \sin(\omega_0 t + \phi)],
\]

Both the time-dependent energy from Eq. (2),

\[
k_e(t) = \frac{1}{2} \left[ x^2(t) + y^2(t) \right] = \left( \frac{E_0}{\omega_0} \right)^2 \left( 1 - \cos(\omega_0 t) \right),
\]

with maximum value \( 8U_p/\omega_0^2 \), is collision time, the ponderomotive energy of electron in circularly polarized laser field \( U_p = E_0^2/2\omega_0^2 \), and the corresponding maximum electron displacement (transfer to a neighboring ion from Eq. (3)),

\[
k_e = \sqrt{x^2(t_t) + y^2(t_t)} = \frac{E_0}{\omega_0} \sqrt{1 + (n + \frac{1}{2})^2 \pi^2},
\]

for integer \( n \), are independent of the CEP, \( \phi \). For 2-axial molecules,

\[
x(t) = R_n = \frac{2E_0}{\omega_0} \left[ 1 + (n + \frac{1}{2})^2 \pi^2 \right] \cos \phi,
\]

\[
y(t) = 0,
\]

where \( n = (n + \frac{1}{2}) \pi \).

With a two-color circularly polarized laser field,

\[
E_x(t) = E_{01} \cos(\omega_0 t + \phi_1) + \cos(2\omega_0 t + \phi_2),
\]

\[
E_y(t) = E_{01} \sin(\omega_0 t + \phi_1) + \sin(2\omega_0 t + \phi_2),
\]

the CEPs \( \phi_1 \) and \( \phi_2 \) determine the optimal values of \( K_n(t) \) and \( K_n(t) \) for MHOHG. The corresponding laser-induced velocities are

\[
x(t) = \frac{E_{0n}}{\omega_0} \left[ \sin(\omega_0 t + \phi_1) - \sin \phi_1 + \cos(\omega_0 t + \phi_2) \sin \omega_0 t \right],
\]

\[
y(t) = \frac{E_{0n}}{\omega_0} \left[ \cos \phi_1 - \cos(\omega_0 t + \phi_1) + \sin(2\omega_0 t + \phi_2) \sin \omega_0 t \right],
\]

and the displacements are

\[
x(t) = \frac{E_{0n}}{4\omega_0} \left[ 4 \cos \phi_1 - 4 \omega_0 t \sin \phi_1 - 4 \sin(\omega_0 t + \phi_1) \right.
\]

\[
\left. - \cos(2\omega_0 t + \phi_2) - \cos \phi_2 - 2 \omega_0 t \sin \phi_2 \right],
\]

\[
y(t) = \frac{E_{0n}}{4\omega_0} \left[ 4 \sin \phi_1 + 4 \omega_0 t \cos \phi_1 - 4 \sin(\omega_0 t + \phi_1) \right.
\]

\[
\left. - \sin(2\omega_0 t + \phi_2) + \sin \phi_2 + 2 \omega_0 t \cos \phi_2 \right].
\]

Maximizing kinetic energy \( K_n \) with respect to \( \phi_1 \) and \( \phi_2 \) gives the net optimal CEP condition \( \phi_1 = \phi_2 = n \pi + \omega_0 t/2 \). Inserting this condition into \( K_n \) Eq. (4), and maximizing the resulting \( K_n \) with respect to \( \omega_0 t \), gives the result for \( n = 0 \), \( \omega_0 t = \pi /3 \), and \( \phi = \pi /3 \), whereas for \( n = 1 \), \( \omega_0 t = 2\pi /3 \), and \( \phi = -\pi /3 \).

For \( n = 0 \) the choice of phases \( \omega_0 t = 2\pi /3 \) and \( \phi = \phi_1 = \pi /3 \) \( \phi_2 \) \( (n = 0) \) gives, respectively, the following components of \( K_n \) where \( U_p = E_0^2/4\omega_0^2 \):

\[
k_{e1} = \left[ \frac{1}{2} x^2(t) + \frac{1}{2} y^2(t) \right] = \left( \frac{E_0}{\omega_0} \right)^2 \left( 1 - \cos(\omega_0 t) \right),
\]

\[
k_{e2} = \left[ \frac{1}{2} x^2(t) + \frac{1}{2} y^2(t) \right] = \left( \frac{E_0}{\omega_0} \right)^2 \left( 1 - \cos(\omega_0 t) \right),
\]

\[
k_{e3} = \left[ \frac{1}{2} x^2(t) + \frac{1}{2} y^2(t) \right] = \left( \frac{E_0}{\omega_0} \right)^2 \left( 1 - \cos(\omega_0 t) \right),
\]

\[
k_{e4} = \left[ \frac{1}{2} x^2(t) + \frac{1}{2} y^2(t) \right] = \left( \frac{E_0}{\omega_0} \right)^2 \left( 1 - \cos(\omega_0 t) \right),
\]

\[
k_{e5} = \left[ \frac{1}{2} x^2(t) + \frac{1}{2} y^2(t) \right] = \left( \frac{E_0}{\omega_0} \right)^2 \left( 1 - \cos(\omega_0 t) \right),
\]

The second choice for \( n = 1 \), \( \omega_0 t = 4\pi /3 \) and \( \phi = \phi_1 = \phi_2 = \pi /3 \), corresponds to replace \( \phi_1 \) by \( -\phi_2 \) in Eq. (11). Equation (11) shows that the total \( K_n \) is independent of \( \phi_1 \) for both optimal CEPs \( \phi = \pi /3 \). In Figs. 1(a) and 1(b) we show \( K_n \) as a function of \( \phi_1 \) and \( \phi_2 \). Maximum \( K_n \) occurs for \( \phi_1 = \pm \pi /3 + \phi_2 \) as predicted by Eq. (11). However, the different velocities and displacements are functions of \( \phi_2 \) [Figs. 1(c)–1(d)] for \( \phi = \pi /3 \) and \( \pi /3 \). The corresponding x and y components of \( K_n \) are alternate in phase.

At intensity \( I_0 = 2 \times 10^{14} \) W/cm² (\( E_0 = 0.0755 \) a.u.) and \( \lambda = 400 \) nm (\( \omega_0 = 0.114 \) a.u.), the electron displacements (transfer distances) \( x(t) \) and \( y(t) \) for \( \omega_0 t = 2\pi /3 \) and \( \phi = \pi /3 \) \( (n = 0) \) and for \( \omega_0 t = 4\pi /3 \) and \( \phi = -\pi /3 \) \( (n = 1) \) are shown in Figs. 1(e) and 1(f), respectively. With \( \omega_0 t = 2\pi /3 \), for example, for phases \( \phi_1 = \pi /3 \) and \( \phi_2 = 0 \), the electron displacements are \( x(t) = -0.35 \) a.u. and \( y(t) = 0 \) a.u., and for \( \phi_1 = 0 \) and \( \phi_2 = -\pi /3 \), the electron displacements are \( x(t) = -0.84 \) a.u. and \( y(t) = -0.57 \) a.u. from Eq. (10).

Maximum efficiency of the MHOHG process is obtained for the smallest \( x(t) \) or \( y(t) \) which corresponds to near direct (head-on) collision with a neighboring nucleus. Thus at \( \lambda = 800 \) nm (\( \omega_0 = 0.057 \) a.u.), the corresponding electron displacements are, respectively, \( x(t) = -1.4 \) a.u. and \( y(t) = -0.74 \) a.u. and \( x(t) = -0.64 \) a.u. and \( y(t) = -0.57 \) a.u. We conclude hence that short wavelengths (e.g., \( \lambda = 400 \) nm) and
with the laser-induced electron acceleration obtained from the exact time-dependent electron wave function $\Psi(r,t)$:

$$\rho(t) = \langle \Psi(r,t) | -\partial / \partial r | \Psi(r,t) \rangle.$$ (16)

For the ten-optical-cycle pulse used here, the HHG spectra calculated from the FT of dipole moment, velocity, and acceleration forms give nearly the same results [28].

To describe the polarization properties of the emitted MHOHG [29], the relevant physical quantities are introduced (see, for example, Fig. 1 in [22]). The complex integral in Eq. (15) has two $x$ and $y$ components, thus allowing us to extract the dependence of the phase difference $\delta$ between the polarized component of the emitted harmonics on the angular frequency $\omega$ [50]. The ellipticity $\varepsilon$ and the orientation angle $\phi$, the angle between the major axis of the ellipse and the $x$ axis, are defined, respectively, as

$$\varepsilon = \tan \chi$$ (17) and

$$\tan(2\phi) = \tan(2\gamma) \cos \delta,$$ (18)

where

$$\sin(2\chi) = \sin(2\gamma) \sin \delta,$$ (19) and

$$\tan \gamma = \sqrt{P_x/P_y}.$$ (20)

IV. NUMERICAL RESULTS AND DISCUSSIONS

The numerical results in Fig. 2 based on solutions of the $x$-aligned $H_2^+$ TDSE, Eqs. (12)-(14), with a single circularly polarized laser pulse confirm our conclusion in Eq. (5) where maximum harmonic energy $I_n + M(t)$ is induced. For wavelength $\lambda = 400 \text{ nm}$ ($\omega_0 = 0.114 \text{ a.u.}$) and intensity $I_0 = 2.1 \times 10^{13} \text{ W/cm}^2$ ($E_0 = 0.077 \text{ a.u.}$), Fig. 2 shows the corresponding MHOHG spectrum at the internuclear distance $R = 22 \text{ a.u.}$ corresponding to $R_a = 3.72 E_0 / \omega_0$, Eq. (6) with $n = 0$. The maximum harmonic order $N_m = (I_0 + M(t)) / \omega_0$

![Figure 1](image1.png)

**FIG. 1.** (Color online) Total kinetic $K_r$ as a function of phases $\phi_1$ and $\phi_2$ (radian) for the cases (a) $n = 0$ and $\omega_0 L = 2\pi/3$ and (b) $n = 1$ and $\omega_0 L = 4\pi/3$. The CEPs $\phi = \phi_1 - \phi_2 = \pi/3$ and $\phi = -\pi/3$ give the maximum $K_r = 12.5 I_0$, respectively. The corresponding kinetic energies $K_r$ and $K_r$, Eq. (11) ($\psi_0$, and displacements $x(t)$ and $y(t)$, Eq. (10)) are $O_2$ for the maximum $K_r$ with a dichromatic circularly polarized laser pulse at $I_0 = 2 \times 10^{13} \text{ W/cm}^2$ ($E_0 = 0.0755 \text{ a.u.}$), $\lambda_1 = 400 \text{ nm}$ ($\omega_0 = 0.114 \text{ a.u.}$), and $\lambda_2 = 200 \text{ nm}$ ($\omega_0 = 0.228 \text{ a.u.}$) as a function of $\phi_2$.

**III. COMPUTATIONAL METHODS**

We consider the $H_2^+$ molecular ion at a fixed internuclear separation $R$ (Born-Oppenheimer approximation) interacting with a circularly polarized laser pulse $E(t)$. The corresponding 2D (plane) TDSEs

$$\frac{\partial}{\partial t} \Psi(r,t) = H(r,t) \Psi(r,t),$$ (12)

$$H(r,t) = H_0(r) + r \cdot E(t),$$ (13)

$$H_0(r) = -\frac{1}{2} \nabla^2 + V(r),$$ (14)

where $r = x$ and $y$, $V(r)$ is the two-center Coulomb potential, and the matter-field interaction is treated in the length gauge, are solved numerically by a three-point difference combined with higher-order split-operator methods [26,27]. A temporal slowly varying envelope $\sin^{2}(\pi t/10t_0)$, where one optical cycle (o.c.) $\tau = 2\pi/\omega_0$, is adopted. The MHOHG power spectrum $P_\omega(\omega)$ is obtained from the absolute square of the Fourier transforms (FT) of the dipole acceleration $\langle \rho(t) \rangle$:

$$P_\omega(\omega) = \left| \int \exp(-i\omega t) \langle \rho(t) \rangle dt \right|^2$$ (15)

![Figure 2](image2.png)

**FIG. 2.** (Color online) The $x$ (solid blue line) and $y$ (dashed red line) components of $x$-aligned $H_2^+$ MHOHG at $R = 22 \text{ a.u.}$ for $\lambda = 400 \text{ nm}$, $I_0 = 2.1 \times 10^{13} \text{ W/cm}^2$, and $\phi = \tan(\pi/2)$ circularly polarized light. The cutoff order $N_\omega = (I_0 + M(t)) / \omega_0$.
occurs around \( N_n = 13 \) in both \( x \) and \( y \) directions, with a decrease in intensity for orders larger than \( N_n \). We reemphasize that for equilibrium \( \text{H}_2^+ (R_e = 2 \text{ a.u.}) \) no harmonics are appreciably produced and observed numerically and none for the H atom since the ionized electron never collides with the parent ion.

Figure 3(a) illustrates the MHOHG spectrum obtained for \( \text{H}_2^+ \) aligned with the \( y \)-axis such that \( y(t_c) = -R = -19 \) a.u. and \( x(t_c) = -0.35 \) a.u. at \( I_0 = 2 \times 10^{14} \text{ W/cm}^2 \) (\( T_0 = 0.0755 \) a.u.; \( \lambda_1 = 400 \text{ nm (} n_\text{opt} = 0.114 \text{ a.u.)}, \lambda_2 = 200 \text{ nm (} n_\text{opt} = 0.228 \text{ a.u.)}, \phi_1 = \pi \text{/}3 \text{ and } \phi_2 = 0 \text{ (} \phi = \pi \text{/}3 \)). A plateau is obtained between harmonic orders 10 and 20 with a cutoff (decrease) around the harmonic energy \( T_e + 13.5T_p \). Figure 4(a) shows, with the same pulses but phases \( \phi_1 = 0 \) and \( \phi_2 = \pi \text{/}3 \text{ (} \phi = -\pi \text{/}3 \)), a similar MHOHG spectrum obtained but \( y(t_c) = -R = -37 \) a.u. and \( x(t_c) = -0.35 \) a.u. at collision. In Fig. 5(a), at the same intensity but longer wavelengths \( \lambda_1 = 800 \text{ nm (} n_\text{opt} = 0.057 \text{ a.u.) and } \lambda_2 = 400 \text{ nm (} n_\text{opt} = 0.114 \text{ a.u.) and phases } \phi_1 = \pi \text{/}3 \text{ and } \phi_2 = 0 \text{ (} \phi = \pi \text{/}3 \)), the same maximum harmonic order is obtained: \( N_n = (T_e + 13.5T_p)/\omega_0 \text{ but now } y(t_c) = -R = -74 \text{ a.u. and } x(t_c) = -1.4 \text{ a.u. at collision with the neighbor.}} \)

In Figs. 3(b), 4(b), and 5(b) we show the MHOHG spectrum at the equilibrium distance \( R_e = 2 \text{ a.u. We see the absence of a long plateau with high efficiencies since now collision with neighboring nuclei does not occur, but rather the } \text{H}_2^+ \text{ molecule at } R_e = 2 \text{ a.u. appears like a one-center atom to the ionized electron at larger } x \text{ and } y \). We reemphasize that at
(a) $\chi^{\Sigma^+}_g (\lambda_e=2.75 \text{ a.u.})$
\[ \lambda = 10 \text{ nm, } \text{Re}=1.675 \text{ a.u.} \]

(b) $\chi^{\Sigma^+}_g (\lambda_e=1.65 \text{ a.u.})$
\[ \lambda = 5 \text{ nm, } \text{Re}=1.675 \text{ a.u.} \]

(c) $X^{\Sigma^+}_g (\lambda_e=2.44 \text{ a.u.})$
\[ \lambda = 10 \text{ nm, } \text{Re}=10 \text{ a.u.} \]

$A^{3\Sigma^+}_{uu} (\lambda_e=2.58 \text{ a.u.)}$

$A^{3\Sigma^+}_{uu} (\lambda_e=1.62 \text{ a.u.)}$

HIGHLIGHTS

DOI: 10.1002/cphc.200800770

The Molecular Cat

Maddalena Pedio[b] and Majed Chergui*[a]

One of the often-claimed advantages of core-shell spectroscopic techniques is that they can probe valence orbitals—which are responsible for bond formation and are therefore delocalized over the entire molecular edifice—from atomic-like levels. The initial state of the transition is a (core) orbital that is locations. So, would symmetry be conserved in this case? To answer this question, the authors used a subtle approach. Core levels decay in many cases by emission of an Auger electron, while an electron from a higher orbital fills the initially created core hole. The lifetime of the latter is...
Attosecond photoionization of a coherent superposition of bound and dissociative molecular states: effect of nuclear motion

by

André D. Bandrauk,

with S. Chelkowski, G.L. Yudin,
Université de Sherbrooke, Canada

P.B. Corkum (Ottawa),
J. Manz (Berlin)

J Phys B 42, 134001 (2009)
We solved the TDSE for a series of delays: $t_{\text{del}} = 0.5\text{fs} + k \ T_1 / 8$, $k=0,1,.. \ T_1=2\pi/\omega_p$. We calculated the forward and backward) photoelectron spectra $S(p)$, $T1/8=0.46\text{fs}$
Moving $H_2^+$ and $T_2^+$

- $p = 2.4$ au

- $p = p_{\text{max}} = 2.2$ au

Asymmetry:

$$\text{asymmetry} = \frac{S_{\text{forw.}}(p) - S_{\text{backw.}}(p)}{S_{\text{forw.}}(p) + S_{\text{backw.}}(p)}$$
Decoherence ?: see Zurek, PRD 47,488(1993)

We show the initial $v=0$ vibrational state and the dissociating packets on $\sigma_u$. Conclusion: at $t>3$ fs ($t_{\text{del}}>1.5$ fs) we loose the overlap in $H_2^+$. This agrees with the attenuation seen in the previous slide.
Fig. 1. Illustration of the pump-probe scheme.

T Bredtmann, (FU Berlin), S Chelkowski, ADB
Fig. 2. (a) nuclear wave packets on three surfaces.
(b)-(c) Harmonic spectra as function of the delay time $t_{\text{del}}$.
Fig. 3. Intensity of selected harmonics as function of time delay $t_{\text{del}}$. 
Fig. 4 Time-profiles for the scheme (l), blue - $t_{\text{del}}=5.0$, green - $t_{\text{del}}=5.2$ fs
Fig. 5 Harmonic spectra for \( I_{\text{probe}} = 4 \times 10^{14} \text{W/cm}^2 \) generated from:
(a) \( \sigma_\text{g} 1s \) (red) and \( \sigma_\text{u} 1s \) (blue), and from:
(b) coherent superposition at delays 1.45, 1.75 and 1.95 fs (scheme III).
Nuclear fusion from explosions of femtosecond laser-heated deuterium clusters

T. Ditmire, J. Zweiback, V. P. Yanovsky, T. E. Cowan, G. Hays & K. B. Wharton

Laser Program, L-477, Lawrence Livermore National Laboratory, Livermore, California 94550, USA

As a form of matter intermediate between molecules and bulk solids, atomic clusters have been much studied. Light-induced processes in clusters can lead to photo-fragmentation and Coulombic fission, producing atom and ion fragments with a few electronvolts (eV) of energy. However, recent studies of the photoionization of atomic clusters are ionized, electrons undergo rapid collisional heating for the short time (<1 ps) before the cluster disassembles in the laser field. Through various collective and nonlinear processes, the laser rapidly heats the electrons to a non-equilibrium state (with mean...
Recollision of $d^+$ with a $\mu d$ atom initiated by a super-intense laser

Recollision energy = 1.40 MeV

$X_T = 0.9$ Å

Electric field $E(t)$ of the laser

Thus the laser can initiate a nuclear reaction, e.g:

$d^+ + d \rightarrow n (2.45 \text{ MeV}) + ^3\text{He} (0.82 \text{ MeV})$

or

$d^+ + t \rightarrow n (14.1 \text{ MeV}) + ^4\text{He} (3.5 \text{ MeV})$
d-\(\mu\)-d molecule dissociating in
200 nm, \(I=10^{22}\) W/cm\(^2\) laser field

probability for \(R<0.25\) \(\mu\) un. (1 \(\mu\) un.=0.0026 Angstrom)

\[26 \times 10^{-14}\text{ m}\)

\[E \sim 1/2\text{ MeV}\]

\[\Delta t \sim 10^{-18}\text{ S}\]

\[=\text{attosecond}\]

PRL 93, 083602 (2004); ADB, G Paramonov, AIP Conf Proc, 1209, 7 (2010)
Dressed Potential Energies for H$_2$ molecule in static laser field

\[ I = 4 \times 10^{14} \text{ Wcm}^{-2} \]

\[ I = 1 \times 10^{15} \text{ Wcm}^{-2} \]

Tracking Electrons

Attosecond science opens the door to real-time observation and control of electron dynamics

Jyllian Kemsley

TEN YEARS AGO, Ahmed H. Zewail won the Nobel Prize for using femtosecond spectroscopy to study atomic motions during chemical reactions. Emerging now from Zewail's pioneering work is the ability to use femtosecond laser pulses to monitor attosecond-scale electron dynamics, which was the focus of a Division of Physical Chemistry symposium on attosecond science at the American Chemical Society national meeting in Salt Lake City last month.

"There's a whole class of processes associated with electron dynamics that occur at a femtosecond timescale or less," Daniel M. Neumark, a chemistry professor at the University of California, Berkeley, said at the meeting. "These are electron dynamics processes that don't require nuclear motion. To probe them you need attosecond-scale pulses."
Mathematical Problems

1. High order SOM
2. Multiscale time frequency analysis
3. Infinite D Optimal Control theory
   (Bartels, Murnane, Rabitz, PRA 70, 043404(2004); ADB et al, PRA 69, 041802(2004))
4. High order NLSE
5. Relativistic QM
6. Molecular movies
   (Dynamic Imaging of Electrons-Nuclei)
Quantum Dynamic Imaging

Theoretical and Numerical Methods

Editors:
André D. Bandrauk, Université de Sherbrooke, QC, Canada
Misha Ivanov, Imperial College London, UK

Studying and using light or “photons” to image and then to control and transmit molecular information is among the most challenging and significant research fields to emerge in recent years. One of the fastest growing areas involves research in the temporal imaging of quantum phenomena, ranging from molecular dynamics in the femto (10⁻¹⁵ s) time regime for atomic motion to the atto (10⁻¹⁸ s) time scale of electron motion. In fact, the attosecond “revolution” is now recognized as one of the most important recent breakthroughs and innovations in the science of the 21st century. A major participant in the development of ultrafast femto and attosecond temporal imaging of molecular quantum phenomena has been theory and numerical simulation of the nonlinear, non-perturbative response of atoms and molecules to ultrashort laser pulses. Therefore, imaging quantum dynamics is a new frontier of science requiring advanced mathematical approaches for analyzing and solving spatial and temporal multidimensional partial differential equations such as Time-Dependent Schrödinger Equations (TDSE) and Time-Dependent Dirac equations (TDDIs for relativistic phenomena). These equations are also coupled to the photons in Maxwell’s equations for collective propagation effects. Inversion of the experimental imaging data of quantum dynamics presents new mathematical challenges in the imaging of quantum wave coherences on subatomic (subnanometer) spatial dimensions and multiple timescales from atto to femto and even nanoseconds.

In Quantum Dynamic Imaging: Theoretical and Numerical Methods, leading researchers discuss these exciting state-of-the-art developments and their implications for R&D in view of the promise of quantum dynamic imaging science as the essential tool for controlling matter at the molecular level.

Key Features:
- Presents the latest research results in ultrastall imaging of quantum phenomena
- Demonstrates the wide-ranging potential of quantum dynamic imaging for R&D in areas as diverse as optoelectronics, materials science, and quantum information
- Edited and written by international leaders in the field

Forthcoming
May 2011
High-Energy QED: Real and Virtual Pairs

Courtesy of CH Keitel(MPI,hdb)

Dirac dynamics of an electron with negative energy in crossed laser beams: pairs from $10^6$ W/cm$^2$
"If you don’t know where you’re going, any road will take you there."

THE CHESHIRE CAT, FROM LEWIS CARROLL’S “ALICE IN WONDERLAND.”
Theoretical approach to reactions of polyatomic molecules

L. Züllicke, A. Merkel
Akademie der Wissenschaften der DDR, Zentrainstitut für physikalische Chemie, DDR-1199 Berlin, German Democratic Republic

ABSTRACT
A scheme for systematic reduction of the theoretical treatment of elementary reactions involving polyatomic molecules is described; it consists of (1) limitation to the energetically relevant regions of the nuclear configuration space (the reaction path and its near environs) and (2) restriction to the dynamically relevant subspace of the nuclear configuration space (the active modes). Starting from a generalized reaction path Hamiltonian of Nauts and Chapuisat allowing for the use of arbitrary curvilinear coordinates and several large-amplitude modes, the realization of the above-sketched scheme is discussed. A compilation of recent work along these lines, mostly based on the simplified Miller-Handy-Adams reaction path Hamiltonian, is given with particular emphasis on applications of a statistical adiabatic model.

Received: 14 February 1989; Accepted: 4 July 1989

10.1002/qua.560380214  About DOI
209 - Science Laser Ultrarapide-Femto-Atto-Zeptoseconde-FAZS

Responsables
Andre BANDRAUK, Université de Sherbrooke
François LÉGARE, INRS

Informations sur le colloque

Catégorie : Colloque

Description du colloque :
La science laser moderne a subi une révolution par la génération d'impulsion ultracourte (quelques cycles optiques) et intense (>10^{15} W/cm^2). Ceci permet l'étude de l'interaction laser-matière dans un nouveau régime hautement nonlinéaire et non-perturbatif. Le Québec est très actif et dominant dans ce domaine grâce à des laboratoires comme ALLS (Advanced Laser Light Source) situé à l'INRS-EMT, le Centre d'Optique, Photonique et Laser (COPL) de l'Université Laval, et l'équipe Atto-Québec financé par le FQRNT, etc. Un réseau de calcul de haute performance, RQHP, membre de Calcul Canada permet d'exécuter des simulations de haut niveau pour guider les expérimentateurs. Ce colloque propose donc de rassembler les acteurs principaux du Québec en plus quelques sommités internationales (françaises) pour adresser les questions importantes d'applications futures à de nouvelles technologies importantes pour la société de l'avenir.

Sessions
Lundi 9 mai 2011

Science Laser Ultrarapide-Femto-Atto-Zeptoseconde-FAZS

08:25 - 12:00
UdeS- Éducation-A2-021
Type : orale
Fs + asec pulses

Harmonic order

20nm

6x10^{13} \text{ W/cm}^2
Rapport annuel 2008
1er janvier au 31 décembre
Many Physical Review articles contain images that not only convey important scientific information, but also are visually pleasing. The editors showcase a selection of images from published articles (read the announcement). The selections are based on aesthetics, not on the scientific merit of the paper. The figures may be slightly modified from the published version. Recently published images also appear on our main page.

Click on each thumbnail to see the full image and link to the paper.