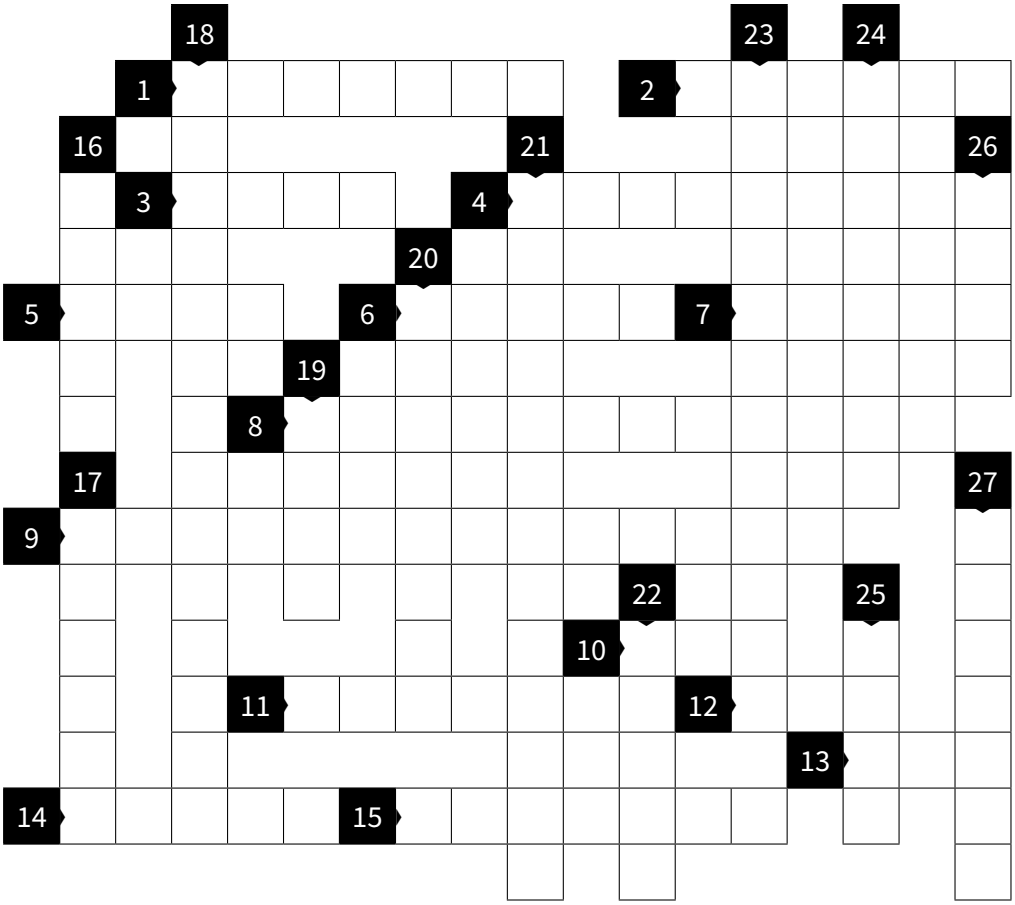
CROSSWORDS
ON NON-LINEAR OPTICS

By Philippe ADAM



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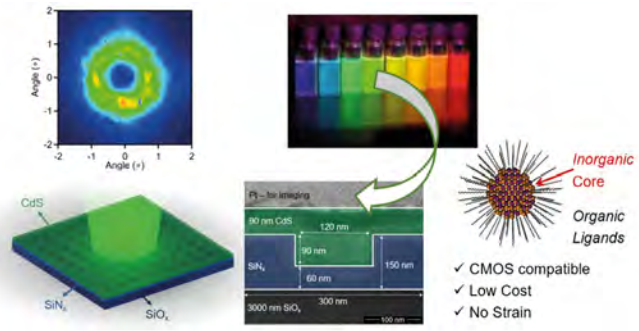
1 A poor lonesome… wave packet
2 Spectral Phase Interferometry for Direct Electric-field Reconstruction
3 Material used for frequency conversion in integrated photonics
4 Third order nonlinear effect
5 Also called quadratic electro-optic effect
6 Laboratory at high… level !
7 A matter of selection
8 Produced by nonlinear refractive index change
9 In other words: CAS 12031-63-9 or electro-optic and nonlinear material
10 Lithium Triborate
11 Very intense light in ELI
12 Non Linear Optics-Acronym
13 Operation possible in wave mixing
14 His name is included in SRS, CARS…
15 Non linear EO effect in materials with lack of inversion symmetry
16 Periodically poled material
17 Optics at low intensity
18 Almost a white laser
19 Must be considered in the angular momentum of light
20 Results from Kerr self-focusing
21 Can only be observed in anisotropic crystals
22 Characteristic energy in atoms or molecular states
23 NLO happens when higher-order terms in electric field are present in its expression
24 Dividing wavelength by two in a crystal
25 Quantity to be minimized to get high response
26 Non Linear Schrödinger Equation-Acronym
27 Soft material able to exhibit non linear effects as well

Optical gain and lasing from bulk cadmium sulfide nanocrystals

Colloidal Quantum Dots are in the spotlight thanks to the recent Nobel Prize in Chemistry. From their beginnings, these tiny wonders have evolved to encompass multiple applications in photonics, like photodetectors and LEDs. A different application the scientific community pursues, their potential integration into lasers, has been a journey marked by steady progress, albeit at a measured pace.



The laser integration challenge boils down to finding materials that strike the right balance—low-threshold, extended inverted-state lifetime, and a material gain coefficient that plays nice with cavity losses, especially under electrical excitation. In a recent Nature Nanotechnology publication from Ghent University, a paradigm shift is presented for this exact application: by shifting from strongly confined nanocrystals to "bulk nanocrystals", in this example made from Cadmium Sulfide (CdS). Despite appearing contradictory initially, this definition is, in fact, not contradictory at all: when the nanocrystal surpasses the Bohr diameter (approximately 6 nm for CdS), it no longer is strongly confinement, and now has the same optical properties as a bulk semiconductor. This can be true, all while maintaining its classification as a nanocrystal, typically referred to as crystals between 1-100 nm. The study unfolds through the lens of ultrafast pump-probe spectroscopy, revealing that these bulk nanocrystals boast not only a solid material gain but also showcase top-tier lifetimes and surprisingly low thresholds, surpassing all other colloidal materials in existence.

The significance of these findings can have far reaching consequences, hinting at future dominance of bulk nanocrystals in the realm of efficient lasing from solution-processable materials. The future is extremely bright for bulk colloidal nanocrystal based lasers.

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USING INTENSE ULTRASOUND IN AMBIENT AIR TO CONTROL HIGH PEAK POWER LASER PULSES

Optical elements used in modern photonics are almost entirely based on the interaction of light with solid media. However, limitations imposed by various parameters, including optical wavelength and power, arise from the properties of these solid media. In an attempt to circumvent these limitations and extend the range of controllable parameters, a promising approach is to omit the solid medium altogether.

In their recently published paper, scientists from collaborating German institutes demonstrate how sound waves in ambient air can be used to control light. Their innovative approach relies on high-intensity ultrasound, comparable to the sound pressure level of a jet engine. They have experimentally realized a gas-based AOM without any transmissive solid media and with already high deflection efficiency (50%). Their numerical simulations suggest that much higher deflection efficiencies should be possible at slightly higher sound pressure levels.

The scientists see great potential in the generalization of this 'Gas-Phase Sono-Photonic' method, as they have already demonstrated control over peak powers of 20 GW, about three orders of magnitude higher than previously possible. Promising directions could include overcoming spectral limitations and, in the future, extending the approach to other optical techniques such as gas lenses or waveguides.

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Interview with Basil Garabet, CEO of NKT Photonics

NKT Photonics is a company providing fiber lasers and photonic crystal fibers.

How and when was NKT Photonics founded?

NKT Photonics originates as spinouts from the Technical University of Denmark funded by NKT Holding, a company founded in 1891 in Denmark that was created to construct cables for Denmark's electrification. The company has grown to become a major company in Denmark's industrial landscape, specializing in electricity, power, and telecommunication cables. In the 1980s, NKT's venture into optical cable production set the stage for a transformative journey. Notably, the collaboration between NKT and AT&T resulted in LYCOM, later assimilated into Lucent Technology.

NKT became a large holding company acting as an incubator for small companies, notably Crystal Fibre and Koheras. These two companies were pioneers in the field of photonic crystal fibers and fiber lasers, and, in 2009, merged to establish NKT Photonics. Amid this evolution, additional acquisitions further solidified NKT's presence. My role in 2015 involved unifying these diverse elements and steering the company toward a paramount position in the photonics realm. Now, the NKT conglomerate is distilled to two key entities: NKT Cables (a publicly traded company) and NKT Photonics. NKT Photonics has recently been acquired by Hamamatsu of Japan, this acquisition awaits approval from the Danish government.

Can you describe the core of your technology?

At our core, we are trailblazers in the realm of photonic crystal fibers (PCFs). Initially, the notion was for

NKT to morph into a telecommunications entity with PCFs at its heart. Koheras, a company developing fiber lasers, came into the picture. Ultimately, NKT's merger of Koheras and Crystal Fibre solidified our focus. Our bedrock revolves around PCFs and lasers derived from them. This translates into the development and commercialization of supercontinuum lasers (the world's largest supplier), single-frequency lasers, and ultrafast lasers. Moreover, the acquisition of the Swiss firm Onefive a few years ago augmented our expertise with solid-state laser technology.

Where are your production facilities situated?

Currently, our production landscape comprises several nodes. Our ultrafast lasers grounded in solid-state technology are crafted in Zurich. For aerospace and defense applications, encompassing multi-kW lasers, production transpires in Southampton. Meanwhile, all other products, including PCF ultrafast lasers, single-frequency lasers, and supercontinuum lasers, are manufactured in Denmark.

What are the primary applications of your products?

We are operating in 4 segments: biomedical imaging and life science, quantum and nano technology, aerospace & defense, industry. Bioimaging & life science is the segment that features the fastest growth while the industrial segment is our largest market. Life science encompasses fluorescence imaging, high-resolution microscopy and ophthalmology with lasers for cataract surgery. The industrial area includes optical tools for semiconductors (e.g. metrology, lithography, quality control). Semiconductor industry operates 24|7 and requires reliable and stable products. Quantum nanotechnology is the most disruptive technology with a very dynamic scientific community involved in making the transition from fundamental science to applications. Nanotechnologies in general are very interesting for our products for characterizing nanomaterials such as 2D materials, quantum dots, plasmonic nanostructures with supercontinuum sources. Within the defense sector, we are mainly focusing on directed energy solutions. This includes multi kW fiber lasers and high-power fiber delivery for the effectors as well as target tracking lasers. Finally, we are participating in projects for space applications mainly involving systems for satellite communication.

What percentage of your budget is allocated to research and development?

Research and development constitute a substantial commitment, ●●●

NKT Photonics headquarters in Danemark

with approximately 20% of our budget channeled into these critical endeavors. Our focus remains on innovating new products aligned with our core technology, predominantly centered around photonic crystal fibers.

How do you identify the potential application areas for your products?
The scalability is a key parameter for identifying new markets. This explains why we are fully involved into quantum technology for instance, since this market is growing fast and will be a key part of the future technology in a wide range of applications. It also matches our product and technology capabilities very well, enabling us to develop unique solutions for that market. We do not aim at covering all the applications of photonics and do not want to invest into markets where other companies are well implanted. We like to be pioneers, to be the firsts. This explains why we do not do cutting, welding machines for example, since these markets are too crowded.

Do you collaborate with academic institutions and research centers?
Given the inherently innovative nature of our products, we are running several PhD programs with different universities. We have established collaborations in Denmark, UK, and Germany.

Are you focusing your sales efforts in Europe or worldwide?
Our market landscape extends worldwide with obviously emphasis in Europe and US. The acquisition by Hamamatsu will open novel doors in Asia. The largest market remains Europe that represents more than 50% of market.

You currently serve as the President of EPIC. What strategies can be implemented to enhance the photonics industry in Europe?
The difference between Europe and US/Asia is that Europe is very fractured. There are many countries that contribute to different areas in photonics and it is a problem. We believe there are not enough investments in photonics in Europe. There are a lot of talented researchers, but many leave Europe.
In EPIC, we are trying to foster the investments and to keep this great technology in Europe. We do not manage to keep leaders in a technology and we need to reverse that trend. The European government (including Denmark) invests less in high technology -including photonics- than agriculture.
EPIC is already good for networking. It is a very efficient industrial organization for bringing different companies together). If we just do that, that will be great, but we can go further by increasing investments in education and collaborations between countries. We need to allow photonics to move much faster than it did in the past. Former people involved into EPIC governance did the same thing in the past. We are just continuing the progress.

How do you envision the next two decades for your company and the global photonics market?
Regarding the company, it has been growing very fast and became a major player in the market. With the emphasis in R&D, we want to become a major company in the different markets in which we are involved. We want to push in the areas where we are in while keeping our eyes open for novel opportunities. Regarding the overall market of photonics, it will gain in maturity with the emergence of large and stable companies. At this stage, the market in photonics is still relatively immature and remains very fragmented. There are thousands of small companies. However, as an industrial customer, it is difficult to depend on small and fragile companies. We can expect more consolidations to get strong companies. ●

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Chemistry Nobel Prize Celebrates Colloidal Quantum Dots: Highly-Engineered, Spectrally Pure Light

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The Chemistry Nobel Prize of this year has been awarded to Alexei Ekimov, Luis Brus, and Moungi Bawendi for their significant contributions to the discovery and synthesis of colloidal quantum dots. What initially started as a strategy to explore the physics of reduced dimensionality in matter has transitioned over the past 40 years into a commercially available technology platform, the largest of which provides red and green color sources for displays. In this overview, we will delve into this transition process and the pivotal roles played by the laureates.

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Early in the development of quantum physics, the concept of confinement emerged when materials reached the nanometer scale. At such scales, the optical absorption and emission spectra of nanoparticles was expected to differ from that of bulk materials. However, for a long time (until the 1970s), low dimensionality remained a theoretical concept.

The first breakthrough came with the development of molecular beam epitaxy, which enabled the growth of high-quality semiconductor thin films. Under specific conditions, it is possible to achieve lattice matching between two materials with different band gaps, allowing them to be grown on top of each other. This energy offset was utilized to create structures confined in a single dimension coined *quantum wells* and, later, three-dimensionally confined systems as *quantum dots*. This innovation was a game-changer for light control. Prior to this, controlling the band gap and emission spectrum of a semiconductor was a metallurgical challenge involving the creation of alloys. Two semiconductors could be melted to form an alloy with an optical band gap generally intermediate to those of the initial components. Instead, quantum confinement allowed tuning the band gap using geometric factors while keeping the composition unchanged. This

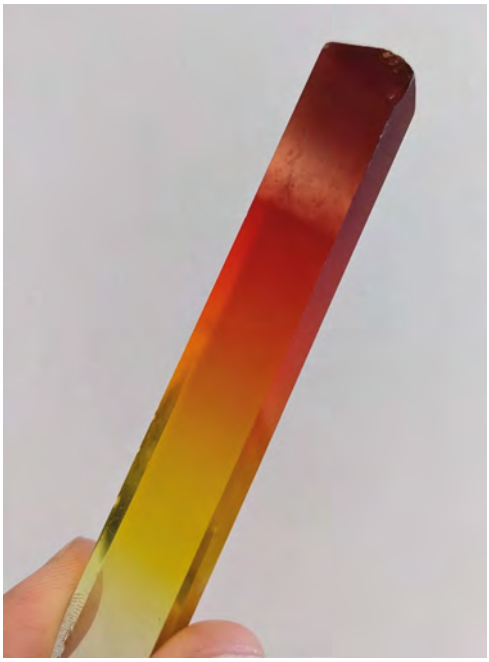

Figure 1. Image of a glass slab grown by Ekimov containing CdSe centers. The thermal treatment conducted on the glass leads to the formation of CdSe quantum dots with various sizes due to the temperature gradient, resulting in a gradient of sizes. Quantum dots at the top are large, resulting in a narrow bandgap and in absorption of almost all visible light. Quantum dots at the bottom are small, pushing their absorption spectrum to the blue resulting in enhanced optical transparency of the glass. Picture Los Alamos National Laboratory, LA-UR-23-31622.

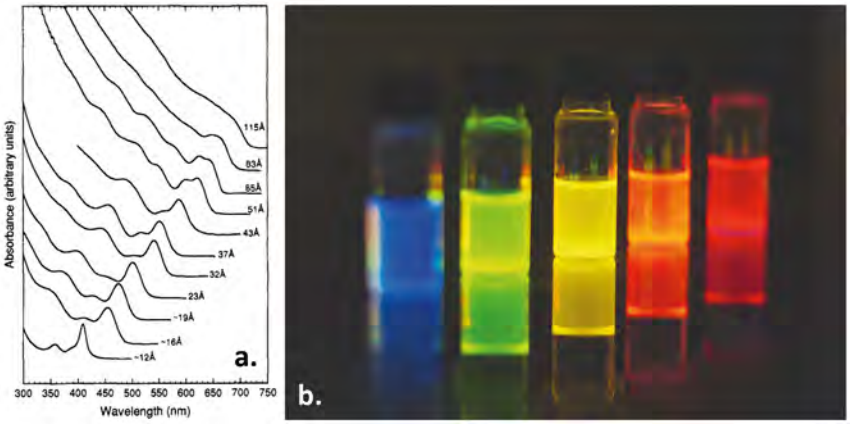

Figure 2. Absorption Spectra of CdSe quantum dots obtained by the hot-injection method as proposed by Bawendi's group in 1993. Figure a is adapted with permission from ref [3]. Copyright {1993} American Chemical Society. b. Image of nanocrystal solutions with various sizes. Nanocrystals are excited with UV light, and what is seen here is their characteristic photoluminescence, peaking at different colors for different sizes.

involved obtaining semiconductors smaller than the exciton Bohr radius, typically a few nanometers for most semiconductors. Epitaxially grown structures utilizing quantum confinement found applications in designing quantum well-based lasers, especially to cover the near-infrared region and its associated telecom applications. It was also employed in the design of quantum well infrared detectors. With the rise of quantum cascade lasers, quantum engineering reached its most complex realization to date.

Despite this success, epitaxy remains a complex method, characterized by its low throughput and high cost. Additionally, the presence of a lattice-matched substrate constrains the library of available materials and renders them incompatible with certain applications, such as trackers in biological media. Therefore, alternative methods have been explored to obtain quantum-confined luminescent materials [1].

In the 1980s, Alexei Ekimov, working at the Vavilov State Optical Institute, investigated the emission properties of metal halide materials while growing them within a silicate matrix [2]. He observed optical features similar to those of bulk materials but shifted towards higher energy. Ekimov, aware of developments in epitaxially grown heterostructures, attributed this effect to quantum confinement. This attribution was confirmed by measuring the particle size using small-angle X-ray scattering [3]. Using the same strategy, he was able to obtain CdSe (see fig. 1), CdS, as well as GaP nanocrystals in glass matrix [4]. However, those materials only displayed weak light emission at room temperature due to a large number of defects in their structure.

Around the same time, and under the suggestion of Alexei Ekimov, the formalism for calculating optical transitions in isolated, nanoscale, quasi-perfect spheres of semiconductors, was developed by Alexander Efros working at Ioffe Institute [5]. This seminal paper would lay the foundation of the theory to be used in the 40 years to come.

Two years later, the team led by Brus at Bell Labs explored a completely different approach, attempting to grow nanoparticles in a liquid medium. Their initial focus was on CdS [6], and the early concept of colloidal synthesis relied on water-based methods. They successfully described the spectrum using an effective mass approximation while also taking into account the electron-hole interaction [7]. They also observed a shift in the optical features toward higher energy, but these features were not immediately attributed to quantum confinement. During this time, Moungi • • •

Figure 1. Group photo from the Conference "30 Years of Colloidal Quantum Dots" taken during the 2014 conference held at ESPCI to celebrate the 30th anniversary of quantum dots. The three 2023 Nobel Prize laureates' are highlighted with medals.

Bawendi, a postdoctoral scholar working in Brus' team, obtained a position at MIT. There, along with two graduate students, Christopher Murray and David Norris, they developed a new chemical method for colloidal particle growth, known as the hot-injection method [8].

There were two main changes compared to the previous synthesis developed at Bell Labs. Firstly, the team of Bawendi switched to organic solvents, and secondly, they introduced ligands. These surfactant molecules played a critical role in particle growth. By making the surface less available, the growth kinetics could be adjusted, giving a precise control of the nanoparticle size. Furthermore, ligands facilitated interactions with the solvent, maintaining particle colloidal stability. They also participated in the electronic passivation of the surface, addressing a major issue in such materials. For illustration, a 2.5 nm-sized particle has 80% of its atoms on the surface. This new growth method resulted in reduced polydispersity, allowing the distinction of multiple transitions in ensemble spectra, akin to atomic transitions (see Figure 2).

Although synthetic methods have expanded, including the heat-up approach where all ingredients are mixed at room temperature and then heated [9] as well as the demonstration of core-shell structures [10], the hot-injection method remains the core technique for growing nanocrystals today. The benefits of these quantum dots as light sources quickly found applications in areas such as biolabeling, single-photon sources and displays.

The latter application has been a game changer for colloidal quantum dots, marking a transition from academic laboratories to the industrial world. QD Vision, a spin-off from Bawendi's group, has been a pioneer in this field, enabling the design of robust quantum dots capable of sustaining out-of-equilibrium conditions, high temperatures, and long-term operation (up to 30,000 hours), essential requirements for displays. The advantage of nanocrystals over previous generations of emitters used in displays mainly stems from their narrow photoluminescence linewidth. This results in a broader color palette, particularly in a better green, which is crucial for a market where sports events drive a significant portion of TV purchases.

Thanks to nearly 40 years of development, the synthesis of quantum dots has reached an unparalleled level of precision, in a few examples with an accuracy down to the atomic scale and the capacity to grow a wide range of materials. In 2014, a conference celebrating the 30th anniversary of quantum dots was organized at ESPCI Paris. Among the attendees, the three chemistry Nobel laureates from 2023 were prominently featured in the first line, see Figure 3.

As stated by Prof. Heiner Linke, Member of the Nobel Committee for Chemistry, "we believe that many new applications are still coming". In 2022 QD color conversion on the front face of OLED displays was first commercialized and likely we will see QDs used in color conversion for MicroLED displays in the near future. Bright, color-pure, and energy-efficient quantum dot LEDs are a new light-emitting display technology which is expected to reach the market in the coming years. In 2018, quantum dot infrared image sensors able to achieve military-grade performance at a fraction of the cost of historical technologies were first commercialized and likely will grow into a significant product space in the future. Other prospects include their use as high efficiency color optimizers for agriculture by matching the lighting spectrum with the absorption of plants, where they already have met success in the form of large-scale polymer films encapsulating non-toxic QDs. QDs continue to be made and sold for use in biological imaging and solid-state lighting and it can be anticipated that their use in security inks and spectrometers will emerge. Further fields of potential commercial use of these materials in optoelectronic devices comprise QD solar cells and electrically pumped QD lasers. ●

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Attosecond Science: an emerging field brought to light by the Physics Nobel Prize

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The 2023 Nobel Prize in Physics has been awarded to Anne L'Huillier, Pierre Agostini and Ferenc Krausz "for experimental methods that generate attosecond pulses of light for the study of electron dynamics in matter". In this article, we contextualize their seminal works and their central roles that led to the emergence of a global ultrafast community exploring the frontiers of electron dynamics in dilute and condensed matter.

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In Niels Bohr's model of the hydrogen atom, the electron completes its orbit around the nucleus in just 150 attoseconds (1 as = 10^{-18} s). This astonishingly tiny unit of time is the natural time scale for the movement of electrons in matter, relevant to many processes on the microscopic level, from the first stage of chemical reactions to electrical currents and photovoltaic processes. For a long time, these ultrafast phenomena were inaccessible to experimental study because of the lack of light flashes short enough to freeze electronic movements and record a sequence of events like a stroboscope. The discoveries and experiments of Anne L'Huillier, Pierre Agostini and Ferenc Krausz in the 1980's to early 2000 revolutionized ultrafast physics and opened up the field of attosecond science.

Soon after the invention of the pulsed lasers, in the 1960's, a laboratory was settled at the "Commissariat à l'Énergie Atomique" (CEA) in Saclay (France), headed by Gérard Mainfray, to study the interaction between intense lasers and matter (now the Lasers Interactions & Dynamics Laboratory - LIDYL). **Pierre Agostini**, who had joined the laboratory in 1968, investigated multiphoton ionization of atomic gases. An important breakthrough occurred in 1979, when his team observed for the first time "above-threshold ionization", where an atom absorbs more laser photons than required to eject an electron into the continuum [1]. This first observation of continuum-continuum transitions opened up a whole new field of research. Numerous other pioneering studies coordinated by Pierre Agostini followed, laying the foundations for the temporal characterization of attosecond pulses that would be achieved 20 years later.

But before that, and soon after this first landmark, in 1982, **Anne L'Huillier** joined the CEA laboratory, first for her doctorate on multiple ionization of atoms by intense picosecond laser pulses, then as a full researcher. While, in the mid-1980s, the trend of the community was to detect and study the charged particles, ions and electrons, produced through that interaction, she decided to measure also the emitted light. Expecting incoherent ●●●

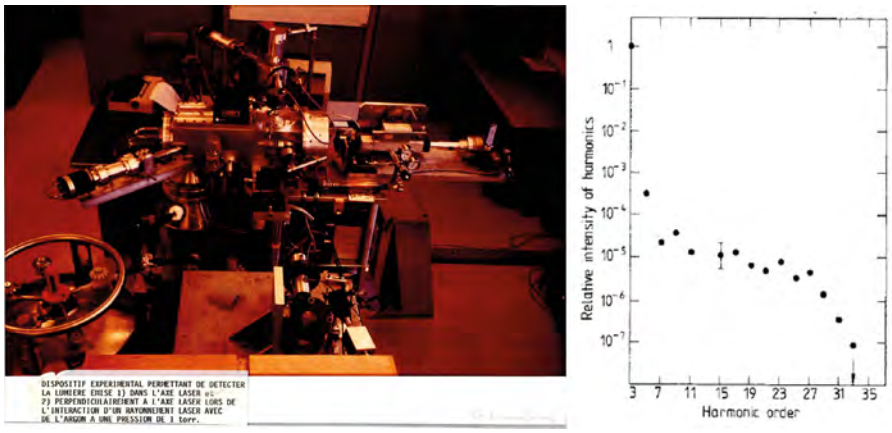
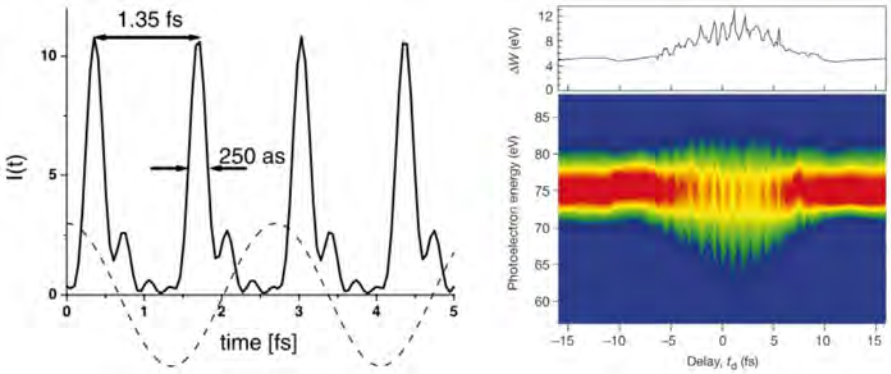


Figure 1. (left) Picture of the first spectrometer used by Anne L'Huillier and coworkers to measure their first published HHG spectrum (right).

fluorescence that would inform about involved excited atomic states, she discovered a neat light beam with a wide range of new frequencies that are multiples of the laser fundamental frequency. This process, known today as High Harmonic Generation (HHG), converts the infrared pulses into the extreme ultraviolet (XUV). In the pioneering publication [2], a spectrum extending up to the 33rd harmonic was detected, spanning 10s of eVs in photon energy. Anne L'Huillier immediately realized the potential of this new XUV light source to complement the existing synchrotrons, stating in the article's conclusion: "Therefore, such an XUV generator [...] could be efficiently used for the general purpose of XUV spectroscopy".

It was soon recognized that the extreme XUV bandwidth from this process could sustain attosecond pulses – if it were coherently generated, and if all the frequencies could be synchronized to constructively interfere in time. Indeed, the minimum duration of a light pulse ($\Delta\tau$) is determined by the width of its spectrum (ΔE, in photon energy) through the time-bandwidth product, $\Delta\tau \cdot \Delta E \leq \hbar$. This fundamental limit states that a 100-as pulse duration requires a minimum bandwidth of 18 eV, the equality being valid for a Gaussian spectral shape, with equal phases for all spectral components. The question of the synchronicity of the XUV high-harmonics then became central to the emerging community. But the answer was not straightforward as the process was poorly documented, and the theory was not developed. Anne L'Huillier and her group thus undertook systematic experimental as well as numerical studies of the phenomenon. The XUV spectrum was extended up to the 135th harmonic, and the yield of the process was optimized, notably through the crucial role of phase-matching of the very many single-atom-emitters in the gas medium. The experimental and theoretical knowledge of HHG rapidly progressed in the early 1990's, attracting ever more research groups and leading to a theoretical breakthrough. In 1993, the first model of HHG was put forward simultaneously by Kenneth Kulander *et al.* [3], and by Paul Corkum [4]. They reckoned that, during the duration of a single oscillation cycle of the strong driving laser field, an outermost electron of the atom is tunnel ionized, subsequently accelerated by the laser field in the continuum, and finally driven back to re-collide and recombine with its parent ion. During the recombination, the electron's energy is released as an XUV photon, responsible for the observed HHG spectra. Just a year later, the derivation of the quantum version of this model [5] was led by Maciej Lewenstein, who at the time was on a sabbatical with Anne L'Huillier at CEA-Saclay. With further refinements over the years, this remains today the most popular framework to model and understand HHG. Building on this model, in 1996, Anne L'Huillier and co-workers could compute the expected phases of the different harmonics, and showed that, in specific generation conditions, attosecond pulses should indeed be obtained [6]. The race towards their first observation was then open, and marked by three parallel key developments. From 1994 onwards, **Pierre Agostini**, in collaboration with Harm Muller (FOM Institute in Amsterdam), built an experimental program aimed at characterizing the duration of ultrashort XUV light sources. With

Figure 2. First measurements of attosecond pulses. A. Attosecond pulse train reconstructed using the RABBIT technique by Pierre Agostini and coworkers [8]. B. Photoelectron Streaking trace measured by Ferenc Krausz and colleagues [10] showing fast oscillations with respect to XUV-IR delay evidencing an isolated attosecond pulse.



colleagues at LOA (Laboratoire d'Optique Appliquée) in Palaiseau, they superimposed XUV light from the new HHG source with a fraction of the fundamental laser inside a photoelectron spectrometer. In addition to electrons ionized via the absorption of single XUV photons, they also detected electrons with their energy shifted by the laser-induced continuum-continuum transitions that Pierre Agostini had discovered 15 years earlier. Since these electrons only appear when both light pulses interact simultaneously with the ionizing atoms, they encode a cross-correlation of the XUV and laser pulses on the femtosecond time scale.

The step onto the attosecond scale came with the second development, initiated in 1996 by a team of theorists from the Laboratoire de Chimie-Physique-Matière et Rayonnement (LCPMR) at Sorbonne University, led by Alfred Maquet. Based on this theoretical work, it was realized that, within this cross-correlation trace, the number of energy-shifted photo-electrons is modulated by the laser-XUV delay, with a period of half a laser cycle [7]. This changed the perspective from modulating XUV-ionized photoelectrons with a laser pulse of femtosecond duration, to modulating with the laser *field*, which varies on the attosecond time scale. These modulations result from interference between different ionization pathways involving successive XUV harmonic orders, and therefore depend on their relatives phases. This led Muller and Agostini to the development of a method called RABBIT ('Reconstruction of attosecond beating by interference of two-photon transitions') that measures via a fine scan of the XUV-laser delay the XUV spectral amplitudes and phases. A Fourier transform then yields the attosecond XUV pulse profile. Implementing this electron interferometry required great stability and a high repetition rate, which Agostini found at LOA, who had just built one of the most advanced femtosecond laser systems of the time and an associated HHG source. This collaboration demonstrated the first measurement of a train of 250-attosecond pulses [8].

The third key development was the rapid advancement of femtosecond laser technology to its ultimate limit, *i.e.* light pulses containing barely a single field oscillation cycle. **Ferenc Krausz**, then at TU Vienna and at the forefront of this work, built lasers producing intense pulses containing only 10 cycles of red light. He invited Mauro Nisoli from Politecnico di Milano, who in 1996, together with Orazio Svelto and Sandro de Silvestri, had shown how to compress such pulses further. They had spectrally broadened the laser bandwidth through nonlinear propagation in a gas-filled hollow-core fiber, before resynchronizing the newly formed spectral components, initially with a prism compressor. In Vienna, Krausz proposed to replace the prisms by so-called "chirped mirrors", which allowed a more fine-tuned compression and led to pulses of 4.5 fs, *i.e.*, less than 2 cycles [9]. With only a single oscillation cycle strong enough to drive HHG, this allowed generating the first isolated attosecond pulses in Vienna. In 2001, Ferenc Krausz's team then met the challenge to characterize them with the help of • • •

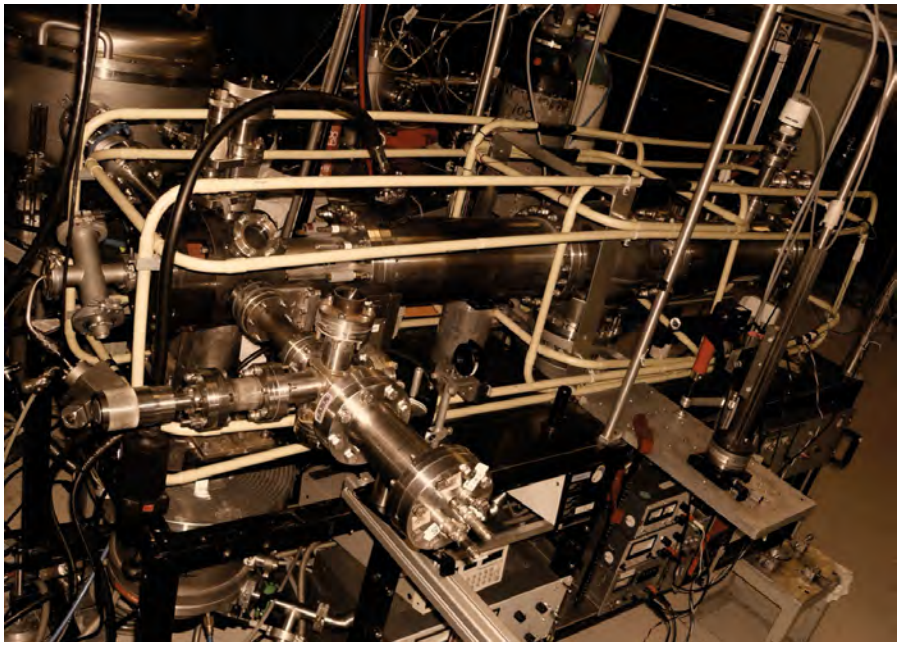


Figure 3. Picture of the magnetic bottle electron spectrometer used by the team of Pierre Agostini to detect the first attosecond pulse trains. This spectrometer is still currently operated on the ATTOLab facility of LIDYL.

Paul Corkum, by an approach related to RABBIT but using a much stronger laser field to act like a streak camera on the photoelectrons ionized by the attosecond pulse. This resulted in the first measurement of an isolated attosecond pulse of 650 as duration [10]. Such pulses became fully reproducible 2 years later when the laser field oscillation inside the pulse envelope was fully controlled by stabilization of the carrier-envelope phase [11], using the frequency-comb technique pioneered by another Nobel Prize winner, Theodor Hänsch.

This attosecond metrology had an immediate impact, as it paved the way both for the continued optimisation of attosecond sources and for their applications. Among the latter, the Nobel Committee highlighted the conceptual advance of time-resolving the photoelectric effect, a process that Einstein had theorized in 1905 through the absorption of a quantum of light (the photon) and the almost simultaneous emission of an electron. The RABBIT and the Streaking methods made it possible to measure tiny emission delays of a few tens of attoseconds. This provided valuable information about the cohesion of matter on a microscopic scale and the complex many-body quantum dynamics, whose theoretical understanding remains one of contemporary physics' major challenges.

The heirs of Anne L'Huillier, Pierre Agostini and Ferenc Krausz have extended the field opened by these pioneers to chemistry, solid-state physics, plasmas and biology. Today, on an international scale, a whole new field, attosecond science, is taking shape with exponential growth. Major investments are being made in the construction and operation of large scale facilities, such as the Hungarian pillar of the European Extreme Light Infrastructure - Attosecond Light Pulse Source (ELI-ALPS) in Szeged-Hungary. At the national scale, attosecond beamlines are already open to users at LIDYL (ATTOLab), ILM-Lyon and CELIA-Bordeaux, within the 'Ultrafast' platform of the national LUMA program, as well as at LOA. The proliferating tools of attosecond science allow observing and controlling the electronic dynamics in strongly correlated materials of interest for future electronic devices, the spin dynamics in magnetic matter, the electronic dynamics in chemistry and biology-relevant molecules, the collective dynamics of plasmas, and are of interest for photovoltaic applications or molecular screening. To fuel these new research paths, source developments are pursued, to industrialize gas phase harmonics, but also to increase their variety through the development of solid state HHG, plasma HHG, or x-ray Free Electron Laser (XFEL) facilities that are now reaching the attosecond frontier. Attosecond science, which began in a handful of laboratories in the 90s, is now emerging as a burgeoning area of research, which has not yet reached its full potential but is developing at a fascinating pace worldwide, spreading into many unexpected areas. ●

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