Interview with Anne L'Huillier

Professor in atomic physics and light-matter interactions, Nobel Prize in Physics 2023 "for experimental methods that generate attosecond pulses of light for the study of electron dynamics in matter".

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How did you discover physics and mathematics?
During my studies, I had always been interested in scientific topics, and particularly mathematics and physics. After high school, I decided to study in a preparatory school for 2 years and selected the Mathematics-Physics line. After these 2 years, I entered the Ecole Normale Supérieure of Fontenay-Aux-Roses, in the south of Paris. During two years, I pursued a dual master degree in physics and mathematics. The third year was dedicated to preparing for a teaching exam in mathematics (agrégation). Then I focused on quantum physics with fantastic lecturers who greatly influenced me. Let me stress that I was not put off by mathematics. I simply wanted to push my knowledge as much as possible in mathematics, with the idea that it would serve my work in physics.

How did you select the topic of atomic physics for your master internship?
What appealed to me with this topic is that you can develop a thorough and fundamental description of light-matter interactions. I did a master internship at the Commissariat à l'Energie Atomique (CEA), in Saclay. At the end, I was offered a PhD position, which I gladly accepted. I joined the multiphoton group led by Gérard Mainfray in 1981 and defended my thesis in 1986. This field of research was at this time very small, and only a few teams in the world were working on this subject because it required intense lasers, which were expensive in the 1980s.

Your career shows that you have never put barriers between disciplines or between theoretical and experimental approaches.
That's true. My studies were 100% theoretical, while my thesis work was very experimental. It was during my thesis that I learned to align a laser beam, manipulate optical beams and master vacuum techniques. But part of my thesis was also theoretical on the interaction between multi-electron atoms and laser light. I think it comes from a desire to maintain some flexibility in my activities and to keep doors open for as long as possible.

What was the major result of your thesis work?
I showed that by absorbing several photons, one atom can be ionized not only once, but several times. In the case of double ionization, we were trying to determine if the 2 electrons were emitted simultaneously or sequentially. I showed that both processes were possible. The essential result of my thesis was published in 1983.

How did you continue your work after your PhD thesis?
After my thesis defense in January 1986, I went to Sweden for a few months to work on the theory of multiphoton ionization of many-electron atoms before being hired in October 1986 by the CEA. We wanted to better understand the interaction between atoms and an intense laser by measuring the emitted light. We developed a new experimental set-up and we could observe the generation of very high-order harmonics (up to order 33) during the summer of 1987. These harmonics had a spectacular behaviour with a plateau distribution from harmonic 7 up to a cutoff.

How was the research group at CEA organized?

There were three teams in the group led by Gérard Mainfray. There was a team composed of Pierre Agostini and Guillaume Petite who were specialists in photoelectron detection. A second team with Didier Normand, Christian Cornaggia and Jacques Morellec worked on resonances using a dye laser and later on molecules. I worked in a third team with Louis-André Lompré and Michel Ferray on measuring ions, and later photons. It was a small unit, and there were many discussions between the teams. My first contacts with Pierre Agostini date back to 1981.

How do you explain the originality of the research carried out in this team?

We had lasers that only a few groups had. We were working on a topic considered very fundamental and which was not seen as a hot topic at the time. Compared to the development of cold atoms, which was an exciting and very promising topic, our studies about atoms in strong laser fields seemed anecdotal and very peripheral. While I was passionate about my research topic, I had no idea that this work would lead me to attoseconds. It was impossible to have this vision at that time.

Did you anticipate the generation of high harmonics?

We knew that it was possible to obtain a few harmonics of orders 3, 5, 7, 9. We were aware of the results achieved by a research group in Chicago that reported the generation of the 11^{th} or 13^{th} harmonic, but with a femtosecond excimer laser at 193 nm that was delivering much higher power than our laser. Let me stress that we were not trying to generate these high harmonics, but rather to study fluorescence. Our result was quite unexpected and fascinating.

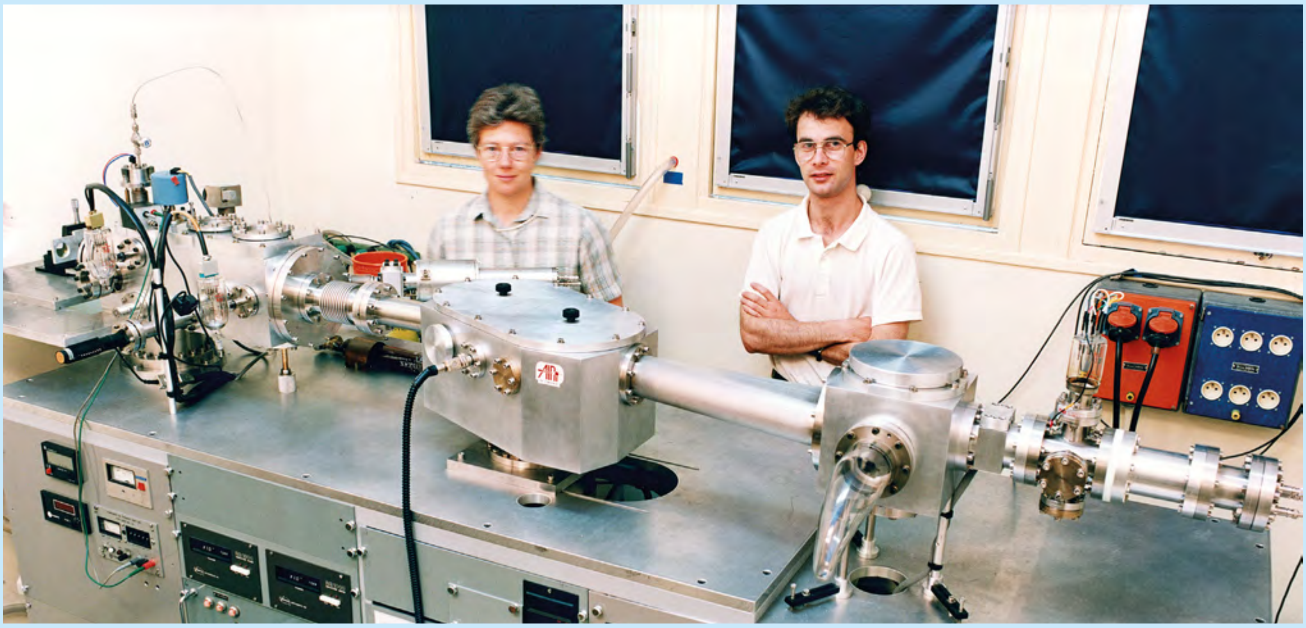
Did you figure out the importance of these results?

We published three articles, but afterwards, my colleagues moved on to developing further the laser towards even higher intensity, by implementing the newly discovered chirped pulse amplification technique, while I continued to work on high-order harmonic generation. I developed collaborations with Kenneth J. Schafer and Kenneth C. Kulander between 1989 and 1991 to describe theoretically the generation of high-order harmonics. In 1989 my first PhD student, Philippe Balcou, started his thesis and we carried out experimental studies.

How did you manage the soar of different laser technologies in the 1990s?

During my PhD thesis at CEA, I worked on 2 types of lasers. A neodymium-doped glass laser and a small Nd:YAG laser. The main laser was the neodymium-doped glass laser, with the 40 ps YAG laser being a small auxiliary laser. It was extraordinary to observe the generation of high-order harmonics with this small laser. We were working at the highest intensity achievable with this laser, and I think we were a bit lucky. After the implementation of the chirped pulse amplification technique at the beginning of the 90s, it became interesting to work with the neodymium-doped glass laser because the pulse duration was much shorter, 1 ps. While this laser allowed us to publish a very important article in 1993 with Philippe Balcou, in which we showed harmonics of order 100 and higher, the experiments took very long time since the laser repetition rate was only 0.1 Hz. When I was offered to carry out experiments in Sweden with a femtosecond Ti Sapphire laser at 10 Hz

Photo of the experimental setup developed at Saclay in 1991 with Anne L'Huillier and Philippe Balcou, her first PhD student.



> ***The fact that Marie Curie existed was a major factor for me. While it took 60 years to have a second female Nobel Prize laureate with Maria Goeppert-Mayer, and 55 more years to the next one, three women have been awarded the Nobel Prize in Physics in the past five years. I think there will be more and more female Nobel Prizes, and this should give hope to young female scientists.***

repetition rate, getting results immediately became much easier. I also traveled to Livermore a few months later to work with a Li:SAF laser.

How did you start working in Sweden?
After my stay in Livermore, I went back to France for working at CEA before leaving again in 1994 for Sweden to join my husband. It was a risky decision because I didn't have a permanent position. CEA was extremely understanding and continued to employ me though I was often in Sweden. This period was certainly complicated on a personal level but very dynamic professionally.

What were the main challenges to generate and to detect attosecond pulses?
The idea of attosecond pulses wasn't so clear, and I was one of the scientists somewhat skeptical about the possibility of generating attosecond pulses. Numerically, we could predict the generation of attosecond pulses only in some particular cases. Another difficulty was to find a method to measure the duration of these pulses. In my group, we had tried for years to measure attosecond pulses using autocorrelation techniques unsuccessfully. Fortunately, in 2001, Pierre Agostini and Ferenc Krausz developed independently cross-correlation techniques and successfully measured the duration of attosecond pulses. Pierre Agostini and his group characterized a train of attosecond pulses with the help of the so-called RABBIT technique, while Ferenc Krausz and his colleagues managed to generate and measure isolated attosecond pulses using few-cycle laser pulses and the streaking technique. When I heard about Agostini's experiment, I proposed to my colleagues to modify our optical setup to perform a similar experiment. We could measure our first attosecond pulses in 2003 (the article was published in 2005).

What have been your main research topics since?
Since 2011, we have worked a lot on the study of the temporal dynamics of the electron emission due to photoionization. Our RABBIT technique approach allows us to understand this electron dynamics in the time domain. My group has grown, and several senior researchers are now working partly with me. While most of our activities belongs to fundamental research, I am also very interested in an industrial application consisting in the metrology of the next generation of integrated circuits using high-order harmonics.

How do you feel about becoming the fifth woman to receive the Nobel Prize in Physics and the second French woman after Marie Curie?
Since the announcement of this Nobel Prize, I have been very busy. Becoming a Nobel prize laureate implies taking on a new task and responsibility, consisting in communicating science, especially to the young generation. I am aware of the additional role I have to play as the fifth woman to be awarded the Nobel Prize in Physics. I believe it is very important to have role models; The fact that Marie Curie existed was a major factor for me. While it took 60 years to have a second female Nobel Prize laureate with Maria Goeppert-Mayer, and 55 more years to the next one, three women have been awarded the Nobel Prize in Physics in the past five years. I think there will be more and more female Nobel Prizes, and this should give hope to young female scientists. ●