

2023 Nobel Prize for physics: a personal view

This year the winners of the Nobel Prize for Physics are Pierre Agostini (Ohio State University), Ferenc Krausz (Max Planck Institute for Quantum Optics) and Anne L'Huillier (Lund University). The motivation for awarding this prize is “for experimental methods that generate attosecond pulses of light for the study of electron dynamics in matter”. The discovery of the attosecond pulses is indeed a milestone in the study of the electron dynamics in matter. However, as they are very difficult to be put in evidence, their existence was initially demonstrated by recording not the temporal but the spectral “face” they show to experimentalists. This is why the first part of the motivation points toward *experimental methods* as the most valuable part of the work of the three Nobel Prize laureates.

The spectral counterpart of the attosecond pulses are the high order harmonics (HH) and these were first measured and characterized. HH are generated in the interaction between an ultrashort laser pulse (duration can be from 4 to 100 femtoseconds) and an atom or a molecule. For simplicity let's take the case of laser pulse interaction with He atom. The electric field of the laser pulse is very intense (due to the short time duration) and is comparable to the Coulomb field which holds the two electrons around the nucleus. At a maximum of the field (imagine a sinus variation of the field) an electron can be extracted from the atom and will be driven away from it. In the mean time the electric field wave will pass through zero and will change sign, starting to decelerate the electron then accelerate it back towards the parent atom. If electron has the chance to recombine with the parent atom, all its kinetic energy gained in his excursion will be transformed into a high energy photon which will be emitted as an attosecond pulse. This simple picture was first formulated by Paul Corkum, a researcher from Canada whose contribution to the field is clearly measurable to the contribution of the three Noble laureates, in my opinion.

Obviously this process happen in every optical cycle of the laser pulse or better to say in the intense ones situated the central part of the pulse. The final result is a train of attosecond pulses emitted twice per optical cycle which in spectral domain translate as a series of equally spaced spectral peaks with frequencies odd multiples of the laser frequency (coming from properties of the Fourier transform). It is this kind of emission which was observed by Anne L'Huillier and reported in 1988 under title “Multiple-harmonic conversion of 1064-nm radiation in rare-gases”.

So, it does not seem to be very complicated to describe the HH generation process. Still, it is studied even today and tons of articles have been written on the subject. This is because the simplicity of the elementary process is a lot complicated when we want to describe the macroscopic process, that is the “simple” experiment in which a laser beam illuminates a gas medium. There the variation of the parameters of the laser and of the medium will produce microscopic sources of attosecond pulses but with different intensities, different emissions in time and different phases of emission. Combining these pulses by interference may be constructive to yield a good signal or destructive to yield weak or no signal. Phase matching proved to be an essential ingredient in getting HH generation efficient.

Since their discovery, HH were investigated in a large variety of experimental configurations: gas in static cells, gas jets, multijets, pure gas (atoms or molecules) or mixed gases. The sources used were mainly

Ti:Sa lasers at 800 nm central wavelength, but also mid-IR going up to 2000 nm (a larger wavelength means also a larger period for the optical cycle, so higher kinetic energy acquired by the electron in its excursion). The group of Ferenc Krausz in Max Planck Institute for Quantum Optics in Garching is one of the leading vectors in this field.

Computer modeling the HH generation in these various configurations was my main field of investigation since 2001. The necessity of HH modeling lies in the need of the experimentalists to explain their data and to uncover the physics behind them. I started building the model at Napoli University in collaboration with Corrado de Lisio and Carlo Altucci, two former PhD students of Anne L'Huillier. I developed many versions of the model in these more than 20 years, and all were used in collaborations with other leading groups of research all over the world: Japan, South Korea, Germany, Hungary, Sweden, Italy, USA. Just to give an example: one of the lines of HH generation in ELI-ALPS was designed by Lund group using the modeling performed in our institute. Also, we used modeling to propose new experiments and predict the results.

One recent version of HH generation is under development at Politecnico di Milano and employs hollow core fibers filled with gas as a generating medium. A dedicated model was developed by us for this special configuration and is used to predict the optimum configuration for the 2000 nm laser which is under construction. This is the topic of H2020 X-PIC project in which our institute is a partner.

The second part of the Nobel committee motivation points toward “study of electron dynamics in matter”. Indeed, this year prize is a validation of the maturity of the attosecond physics, as attosecond pulses are more and more used in the study of the electronic dynamics in gas and condensed matter. The stream of articles in the field moves gradually from those dedicated to optimizing the HH generation to those finding new methods for demonstrating electron dynamics. Applications? Still developing. Let me finish with a quote from Anne L'Huillier: “Will attosecond science be useful to society? My honest answer is: I don't know, but I believe so. Research in attosecond science has been and is still driven by curiosity. Lasers, for example, were not invented to solve a problem. In fact, Theodore Maiman called it “a solution seeking a problem”. No need to describe here the huge impact that the lasers have in our society, for example in medicine or for communications. Attosecond pulses were not invented or developed to solve a specific problem, they were discovered out of curiosity. The future will tell us what impact on society they will have.”

In closing I want to stress that this year Nobel Prize validates also my personal choice which I made 23 years ago. But I am proud enough to say that this choice was validated in time also because this line of research brought in our institute an FP7 and an H2020 project, as well as a number of 7 projects (of which 3 ELI-RO projects) won in national competitions.

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