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Down a Nobel Road
Uncovering the science behind the Nobel Prize in Physics in 2023

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Abstract

The Royal Swedish Academy of Sciences awarded the Nobel Prize to Pierre Agostini, Ferenc Krausz and Anne L'Huillier in Physics in 2023 *"for experimental methods that generate attosecond pulses of light to study electron dynamics in matter"*.

The study of ultrafast electron in matter has become a frontier in modern science, with research dating back as early as the 2000s, driven by the desire to understand these building blocks and to control them at their speeds, ranging about a few attoseconds (10^{-18} seconds), as has been predicted by the calculations of Quantum Mechanics. An electron needs a certain, albeit very short, period to react to the forces of light, ranging to only several tens to hundreds of attoseconds. For the uninitiated, an attosecond is to one second as one second is to the universe's age. This process was considered to be unmeasurably fast – until now.

Attosecond pulse generation, an experimental technique, has emerged as a powerful tool to investigate these ultrafast processes. This article aims to dive into the research of the 3 stalwarts and find out the where, what and how behind their work in the field of Quantum Physics and why their research is worthy of a Nobel Prize. We also explore the potential developments that their work offers in learning more about the behaviour of electrons at such high speeds, be it switching from one energy level to the other or taking part in chemical reactions that form the basis of everything around us.

Keywords: electron behaviour, quantum mechanics, attosecond pulses, pulse generation.

1. Introduction

From our early introduction to Physics or Sciences in general, we know that electrons are the building blocks of matter. They interact with other electrons, jump from one orbital or energy state to another within an atom when provided with or releasing energy and are the currency of exchange between atoms undergoing chemical reactions. With a size of 2×10^{-12} m [1] and a mass of 9.1×10^{-31} kg, these microscopic particles move at high speeds of 2.2×10^{6} m/ sec. These statistics, accompanied by the fact that the distances they cover are microscopic, enable electrons to have a very small reaction time, of the order of tens, hundreds or thousands of attoseconds (10^{-18} seconds). Such high speeds go undetected,

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leaving the behavioural patterns and energy exchanges between electrons in a grey area, shrouded with mystery due to our inability to produce/control light pulses in such short periods.

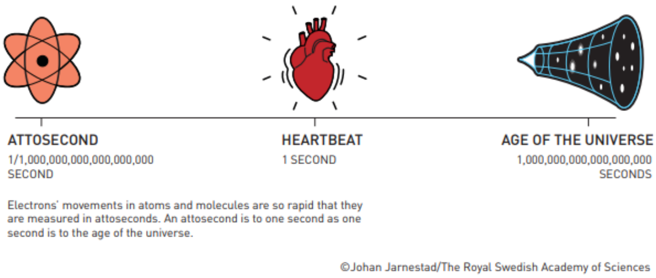

Figure 1: Putting attoseconds into perspective

2. Mechanism

From our real-life examples as basic as the mobile camera, we understand that to capture an event with a brief lifespan, the exposure time of our device's camera must be smaller than the event's lifespan to capture the rapid changes undergone. The faster the event, the faster the snap shot needs to be taken to capture an instant of the event. The same principle applies to all the methods used to measure rapid processes; any measurement must be done more quickly than the time taken for the system being studied to undergo a significant change [2].

In experimental physics, such periods are achieved using lasers that generate light pulses of the order as low as femtoseconds (10^{-15} seconds), and for a good while, various experiments were carried out within this time frame. To discover something at a period smaller than femtoseconds, an upgrade to the existing technology was required to be able to minutely capture the occurrences at a time smaller than a femtosecond.

Since light consists of waves comprising electric and magnetic vibrations passing through a medium, the shortest possible pulse of light is the length of one wavelength of the light wave, the cycle where it swings up to a crest, down to a trough, and back.

As described earlier, femtoseconds were assumed to be the hard limit of this light until the magic of mathematics kicked in, re-establishing the fact that waves of any kind (including any length) can be created if we create corresponding waveforms with enough waves of the exact sizes, wavelengths and amplitudes (distances between successive crests or troughs).

To achieve attosecond pulses, it is possible to make shorter pulses by combining more and shorter wavelengths. This job could not be accomplished by lasers alone; we needed a better medium of interaction and observation, hence gases were introduced. On passing a laser beam through a gas, a significant amount of energy is passed to the atoms and molecules constituting the gas. If the energy is high enough, it can result in electrons being knocked out of their shells, creating ions, hence leading to a process called *laser ionisation of the gas*.

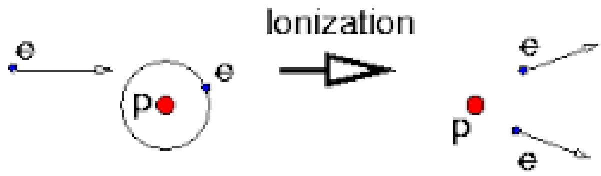

Figure 2: Diagrammatic representation of electrons being pushed out of their orbits due to high energy in-flux

It is to be noted that since light waves are electromagnetic waves, their electric field components switch directions. Thus, an electron knocked out due to the distortion in the electric field keeping it in place, owing to the electric vibrations of the incident laser, can be attracted/ redirected to its parent atom with a change in direction.

Adjacently, the light interacts with its atoms and generates overtones – waves that complete several entire cycles for each cycle in the original wave. These are similar to overtones observed in musical instruments that help us differentiate the same notes of a guitar and a piano due to their distinct qualities [2].

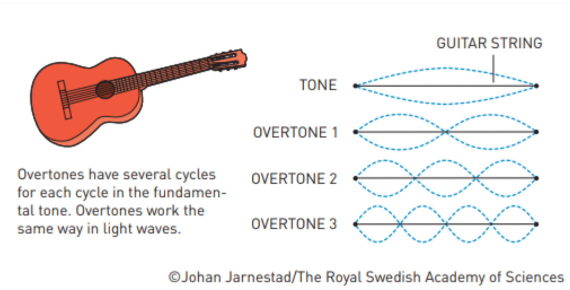

Figure 3: Diagrammatic Explanation of Overtones

In 1987, Anne L'Huillier and her team used this mechanism to their advantage and produced overtones using an infrared laser beam that was transmitted through a noble gas, producing better results than lasers with shorter wavelengths that were used in earlier experiments.

We know that electrons can return to their parent atoms due to changing directions of electric fields/vibrations. Consequently, an electron must lose the energy acquired by it during its expulsion from the parent atom to return to its initial energy level. This excess in energy is released in the form of a light pulse, responsible for producing distinct overtones.

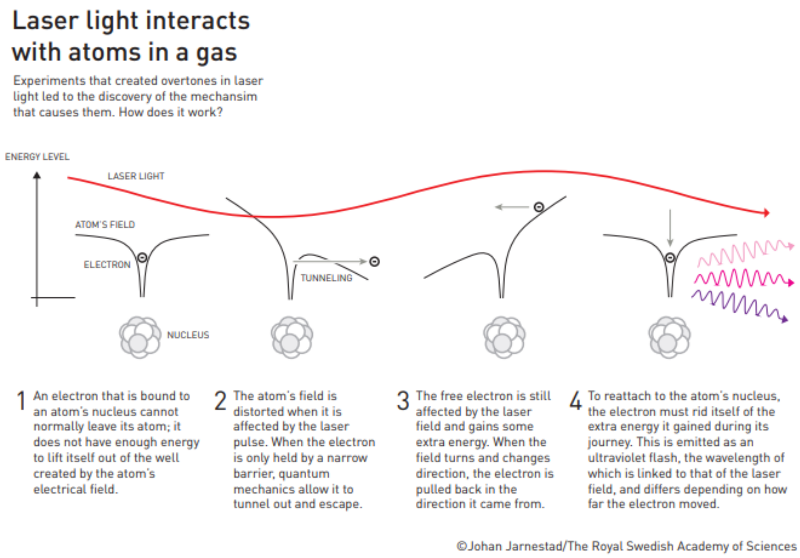

Figure 4: The exchange in the energy of an electron from its expulsion to its re-acceptance by the parent atom

P. Agostini and his group in France produced and investigated a series of consecutive light pulses, like a train with carriages. They used a special method, putting the "pulse train" together with a delayed part of the original laser pulse, to see how the overtones were in phase (displaying the same state at the same time for different waves) with each other. This procedure also gave them a measurement for the duration of the pulses in the train, and they could observe that each pulse lasted only 250 attoseconds.

At the same time, Ferenc Krausz and his group in Austria were working on a technique that could select a single pulse – like a carriage removed from a train and switched to a different track. They succeeded in isolating a pulse that lasted for 650 attoseconds and used it to track and study a process in which electrons were pulled away from their atoms [3].

3. Impact

These experiments, when studied together, guided the scientific community not only towards generating attosecond pulses but also controlling and studying them. Attosecond pulses lie at the core of the mystery shrouding electrons and these experiments shed light on:

1. The time taken to knock an electron out of its orbit,
2. The strong interatomic forces acting on the electron as a measure of the time taken to overcome this force while tearing away an electron from its atom,
3. The oscillation of electrons while moving to and fro in materials.

The findings of these experiments helped overwrite the average positional values of electrons with definitive answers, among other benefits.

4. Discussions

With the ability to measure the activity of electrons in their natural habitat, we are now able to get a peek into the internal workings of matter. It throws light on the interactions of electrons with other subatomic particles, under various conditions such as incident light waves.

The time taken to tear away an electron from its parent atom gives an idea of how loosely or tightly it is bound, the forces experienced by it and the energy required to overcome this force of attraction, most of which was limited to blackboards and notebooks. We can now trace the path of electrons and understand their behaviour under certain conditions or in the absence of these conditions. It gives us the scope to use electrons as a tool that we can control.

Recent developments in attosecond pulse generation have focused on enhancing the pulse energy, duration, and stability. Further research is expected to explore new gas targets, novel interaction geometries, and better pulse compression techniques to improve attosecond pulse quality.

The future of attosecond science holds great promise, including advancements in the study of electron dynamics in biological systems, the development of ultrafast optoelectronic devices, and improved control of chemical reactions on the attosecond timescale.

5. Conclusion

The generation of attosecond pulses has proven to be of utmost importance. These pulses have been used to explore the physics of atoms and molecules in great detail, and they have potential applications in areas ranging from electronics to medicine.

For example, attosecond pulses can be used to push molecules, which emit a measurable signal. The signal from the molecules has a special character, a type of fingerprint that reveals the nature of molecule and furthering research in medical diagnostics.

These impulses are not a full stop but a comma to the enhancement of our experimental boundaries. We may develop better means to understand the constituents of electrons such as quarks, and bosons - particles that have intrigued the scientific conscience in search of manipulating sub-atomic and microscopic particles to undergo reactions to produce new elements or undergo new processes that may be breakthroughs in medicine, in terms of treating illnesses. The road ahead is brighter and noble.

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