Unveiling the Quantum Secrets of Attosecond Radiation

Before the 20^{th} century, it was widely believed that matter consisted of indivisible units called atoms. In 1897 with the discovery of the electron, this paradigm was replaced by the notion that atoms possess internal structure. Since then, scientists have been interested in learning about the atom's constituent parts and studying their dynamics. One of the most prolific techniques to study the internal structure of atoms consists of shining laser light on materials. From the atom-light interaction, we are able to determine the electronic energy levels that characterize different atoms.

On the other hand, electron dynamics inside an atom occur on very small timescales. For instance, processes like ionization, where an electron is released from the atom, take place on a scale of a few attoseconds (10^{-18}s). To truly grasp the astounding brevity of an attosecond, one can think of the following: there are 10^{18} attoseconds in one second, and 10^{18} seconds in the age of the universe. This represents a huge challenge for scientists who seek to study these processes in a laboratory. The shortest laser pulses available have a duration of a few femtoseconds (10^{-15}s). Therefore, they do not provide enough resolution to study electron dynamics. This is analogous to when a picture taken with a camera is blurry because of a long exposure time.

Nevertheless, during the 90s a new way of generating ultrashort laser pulses was observed and thoroughly studied by researchers at the Chicago and Saclay laboratories. These researchers discovered that when you shine a an intense low-frequency laser on a gas sample, you can obtain extreme ultraviolet laser pulses consisting of harmonics of the initial laser. These harmonics are similar to musical overtones, which are multiples of the fundamental note's frequency, except that here the fundamental frequency is that of a light wave instead of a sound wave. Under the right conditions, the obtained laser pulses have durations of the order of attoseconds, making them ideal for studying electron dynamics. The discovered process was named High-order Harmonic Generation (HHG). The 2023 Nobel Prize in physics was awarded to three pioneers in this field: Anne L'Huillier, Ferenc Krauz, and Pierre Agostini for designing experimental methods that generate attosecond pulses of light.

Until recently, it was believed that semi-classical descriptions of HHG, where the atoms are considered as quantum objects and the radiation as classical light, were enough to fully characterize the obtained attosecond radiation. Nonetheless, recent studies show that a full quantum mechanical description reveals quantum features of the attosecond radiation. This new framework can be used to investigate possible implications of different experimental conditions on the attosecond radiation's quantum state. These implications may have an impact on the interaction between the attosecond radiation and the electrons we try to study with it. Thus, it is necessary to fully understand the new quantum description of HHG including the macroscopic effects of different experimental conditions, which haven't been explored in detail yet.

This project aims to understand this new description's fundamental inner workings in the single-atom regime and its macroscopic implications in the many atom regime. To do so, two simulations were written. With the first simulation, the single atom HHG spectrum and the emitted radiation quantum state are obtained using the new theory. With the second simulation, the effects of considering four atoms placed with a given spatial distribution and driven by a Gaussian beam are explored.

Attosecond radiation is a powerful light source that is extensively used to probe electron dynamics inside atoms. For the past 20 years, it has helped uncover a lot of valuable information. Nevertheless, to completely reveal the mysteries of electron dynamics, we must first unveil the quantum secrets of attosecond radiation.