



Nonlinear Attosecond Coherent Control of correlated wavepackets in He Doubly Excited States

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SUMMARY

Understanding electron-electron entanglement is one of the most intriguing challenges of ultrafast quantum physics and helium doubly excited states (DES) offer us with one of the simplest three particles quantum system as a candidate for electron-electron entanglement. Seeded free electron lasers (FEL) provide us with multiple phase-locked harmonics with intense, tunable and fully coherent attosecond pulses. These capabilities could be used for multi photon phase-controlled interferometry schemes like RABBIT and COBRA to study coherent control in Helium DES and eventually entanglement.

Investigating the interaction between electromagnetic radiation and matter is a fundamental step for understanding the internal structure and processes of simple and complex materials. One of the major topics in this research field from the fundamental challenges of quantum mechanics are emergent phenomena such as entanglement and non-local interactions. The development of attosecond pulse trains (APTs) opens up the opportunity for studying the concepts of entanglement and decoherence in quantum systems undergoing ultrafast electronic dynamics. Seeded free-electron lasers (FELs) operating in the extreme ultraviolet (XUV) range such as FERMI have demonstrated the ability to produce intense, fully coherent pulses as well as APTs, with unprecedented intensity and greater flexibility towards the synthesis of tailored waveforms. Coherent control of electron dynamics is one of the stepping stones towards applying the concepts of entanglement. In this context, several beamtimes will be performed at the Low Density Matter (LDM) FERMI beamline using attosecond pulse trains to investigate the coherent control of electronic dynamics in simple quantum systems.

This PhD project is part of the MSCA QU-ATTO Doctoral Network which has the objective of merging the field of quantum optics with attosecond physics through multi harmonic XUV FEL and multi NIR photon interferometry experiments.

This PhD project in particular will try to demonstrate the nonlinear attosecond coherent control of correlated electronic wavepackets in He DES. Previously the spectroscopy of doubly excited, dipole-forbidden states of helium has already been demonstrated at **FERMI**^[1]. These results alongwith the tunability of FEL FERMI will be used to identify these resonances using the central harmonic of a harmonic comb. The control of the excitation will be explored by changing the relative phase of the harmonic comb. The signature of the control will be sought in the photoelectron spectra released after the decay of the doubly excited states. The interpretation of the experimental data will be supported by the group of Alicia Palacios at Universidad Autonoma de Madrid (UAM), where I will do a two-months secondment to learn the theoretical competences to simulate the correlated time-dependent motion of the electronic wave packet excited in the atom using the resources at the supercomputing facility at **UAM**^[2]



Two Schools and two workshops will be organized within the QU-ATTO network:

1. Winter school on communication skills and workshop on training in outreach Activities (at Museo Nazionale della Scienza e della Tecnologia Leonardo Da Vinci in Milan, Italy).
2. Summer School on emerging directions in ultrafast photonics (at FORTH, Heraklion, Greece).
3. Workshop on the the development of nonlinear optical techniques in the XUV and soft X-ray range.
4. Workshop on technology and innovation management by industrial partners of the project.

References:

- [1] M. Zitnik *et al.*, Physical Review Letters 113 (2014)
 [2] A. Palacios, T. N. Rescigno, and C. W. McCurdy, Physical Review A **79**, 033402 (2009).
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Supervisor 1: *Carlo Callegari*

Supervisor 2: *Claudio Masciovecchio*

Supervisor 3: *Alicia Palacios*

List of courses to be taken (pending confirmation)

| Title | Teacher | CFU | Hours |
|--|-----------------------|-----|-------|
| Principles of Free-Electron laser physics | LUCA GIANNESI | 2 | 16 |
| Free electron laser and synchrotron-based spectroscopies: getting to the nanometer with femtosecond resolution | CLAUDIO MASCIOVECCHIO | 2.5 | 20 |
| Advanced data analysis techniques with machine and deep learning | GRAZIA LUPARELLO | 2 | 16 |
| Decoherence in Open Quantum Systems | MATTEO CARLESSO | 2 | 16 |
| | | 8.5 | 68 |

List of interdisciplinary courses to be taken (pending confirmation)

| Title | Course Code | CFU | Hours |
|---|-------------|-----|-------|
| PREPARING A SCIENTIFIC MANUSCRIPT: THE PROCESS, THE CORRECT BEHAVIORS AND THE UNETHICAL SHORTCUTS | DR006 | 1 | 8 |
| POWER POINT: PRESENTATIONS FOR COMMUNICATING YOUR RESEARCH | DR007 | 1 | 8 |
| THE PHD IN PERSPECTIVE: GUIDANCE FOR A MINDFUL CAREER DEVELOPMENT | DR019 | 2 | 16 |
| | | 4 | 32 |



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