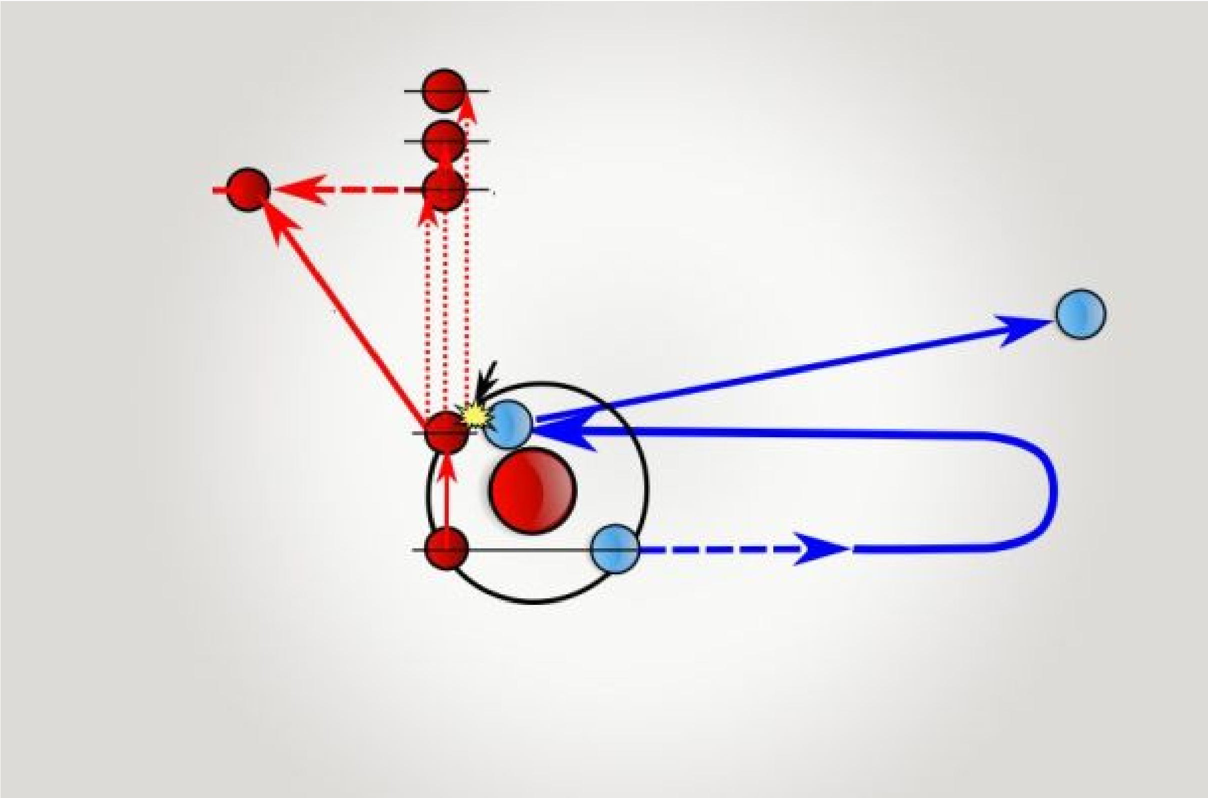

Entanglement reveals itself to Attosecond physics

Researchers from ICFO and Aarhus University report in Nature Communications a novel technique that uses orbital angular moment to detect entanglement in the attosecond regime.

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Entanglement is one of the sweet words we listen to lately when referring to quantum physics. It has provided staggering results in quantum simulations and computing, proving to optimize time in calculations, or even enhance imaging processes. In addition, attosecond physics is the field of physics that studies processes that occur in matter on the scale of attoseconds, i.e. 10-18s the time it takes for electron to move through atoms and molecules. The combination of entanglement techniques and attoscience has led to a new field where attosecond imaging methods exploit quantum phenomena like interference, however the role of entanglement remains unclear/unexplored.

Now, the potential for entanglement to optimize or improve attosecond imaging has been unexplored so far, because, among other things, scientists never assumed that it would have such a leading role in the process. However, in recent years there has been a growing interest in entanglement in attoscience, with a main focus on entanglement between electrons and the ions, because a connection between both has been revealed and scientists have discovered that this phenomenon allows them to better understand the concept of coherence. Most of the focus now has been put in the connection between electrons and ions, but studies on the entanglement between two ionized electrons has received less attention. And those few studies that have actually tackled the issue have based their work on the entanglement of continuous quantities, which are challenging to compute and interpret, and often impossible to measure.

In a recent study published in **Nature Communications**, ICFO researchers **Andrew S. Maxwell, who then transferred to Aarhus carrying this study**, and ICREA Prof. at ICFO **Maciej Lewenstein**, in collaboration with **Lars Madsen** from Aarhus University, have shown that the production and measurement of electron vortex states, which are free electrons with helical wavefront that may carry orbital angular momentum (OAM), offer a solution to the above problems.

In their study, they exploit the discrete degree of freedom, the OAM-inherent to all free particles, to clearly demonstrate the manifestation of entanglement in non-sequential double ionization (NSDI), a highly correlated two-electron ionization process. Through known conservation laws and the superposition of intermediate excited states, they demonstrate that the OAM of the two ionized electrons in NSDI is in fact entangled.

They then use the logarithmic negativity as a way to quantify the entanglement for a wide range of targets and parameters. They construct an entanglement witness, which provides a novel way for detecting the entanglement in an experiment in a much simpler way, avoiding full tomographic measurements. The interplay of intermediate excited states allows the photoelectrons to approach maximally entangled states. Furthermore, the entanglement is robust as it survives incoherent averaging over the focal volume of the laser.

The use of this new technique involving OAM in attosecond processes provides a new pathway for improving imaging technique and learning on how to control matter on ultrafast times scales. Furthermore, the OAM entanglement of the photoelectrons demonstrates the fundamental non-classical nature of NSDI.