Bell Test of Quantum Entanglement in Photoionization

Marco Ruberti[1,2], Vitali Averbukh[1] and Florian Mintert[1]
[1]*Department of Physics, Imperial College London, United Kingdom*
[2]*Max Born Institute, Berlin, Germany*
m.ruberti11@imperial.ac.uk

Photoionization, or photoelectric effect, is one of the universally acknowledged manifestations of the quantum nature of matter that led to the discovery of energy quanta. Less widely appreciated is the fact that it bears the mark of yet another fundamentally quantum concept – the entanglement. When a quantum system, such as an atom or a molecule, is ionized, it is broken up into a pair of quantum-mechanically entangled sub-systems: the emitted photoelectron and its parent ion [1]. The coherences responsible for photoelectron-ion entanglement arise at the attosecond and persist at the femtosecond time scales, underpinning the few-femtosecond charge dynamics in the parent ion [2]. Yet quantum entanglement in photoionization has never been probed and verified yet, e.g. by the celebrated Bell tests.

Here we develop theoretically and simulate numerically a Bell test for probing the entanglement in photoionized systems [3]. We design and simulate the quantum protocol for entanglement quantification for the case of noble-gas atoms photo-ionized by ultrashort, circularly polarized infra-red laser pulses in the strong-field regime, demonstrating robust violation of the Bell inequality. The violation (S > 2) of the Bell inequality we devised is shown in Fig.1 as a function of the emission angle of the photoelectron in the laser polarization plane.

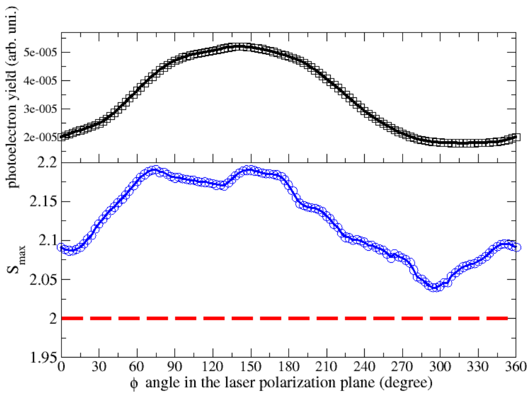

Figure 1: Angle-dependent photoelectron yield (upper panel) and value of the Bell inequality **S** (lower panel) upon photoionization of Ar by a strong circularly-polarized near-IR pulse.

The complete photoionized state is obtained by *ab initio* simulations based on the advanced time-dependent B-spline ADC method [1] with spin-orbit coupling. The Bell test developed in our work [3] detects entanglement between the internal states of the Ar^+ atomic ion and the photoelectron's spin states by exploiting the spin polarization of the photoelectron. This result directly challenges the widely accepted picture of semi-classical dynamics of the photoelectron.

References

[1] M. Ruberti, Phys. Chem. Chem. Phys. **21**, 17584 (2019).
[2] D. Schwickert, M. Ruberti, P. Kolorenč, et al, Science Advances **8** (22), eabn6848 (2022).
[3] M. Ruberti, V. Averbukh, F. Mintert, manuscript in preparation.