# Maximally entangled matter waves with large spatial separation

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Non-classical properties such as a violation of the classical Cauchy-Schwarz inequality and relative number squeezing have been first demonstrated in quantum optics and more recently in pairs of matter waves scattered from colliding Bose-Einstein condensates.
The scattered matter wave has been observed as individual pairs of atoms strongly anti-correlated in momentum, thus readily prepared at large spatial separations. Exquisite experimental control of the pair source with the ability for single-atom detection have enabled applications in ghost imaging [1], and serve as prototypical quantum many-body system that is tractable by particle correlation functions [2].
An open question remained as to if such massive pair source is "quantum" enough to be useful for demonstrating non-locality and testing exotic theories of gravitational decoherence and other collapse theories sensitive to particle's mass and motional degrees of freedom.
We report on a qubit subspace in the triplet of helium-4, in the $2^3S_1$ long-lived excited state, that is isolated and coherently controlled for the first time, with foreseeable extension to achieve complete control of the qutrit itself.
The controllability of the metastable helium qubit and the high internal energy inherent to this atomic species, allow us to demonstrate that the atomic pair source from collisions of oppositely spin-polarised BECs is the archetypal maximally entangled Bell triplet.
A proof-of-concept Bell test was implemented, where we observed a violation of the Bell inequality by 3 standard deviations.
The entangled pairs are used to furthermore demonstrate EPR-steering and are applied to a simple quantum metrology task, namely magnetic gradiometry.

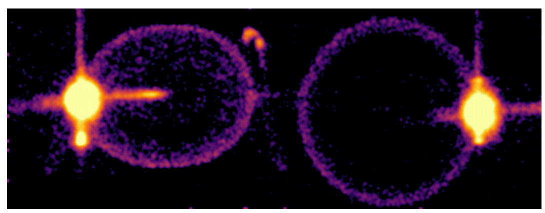

Figure 1: Two collided BECs of opposite spin scatter two faint spherical matter waves (rings), which have been spatially split on the detector by the Stern-Gerlach effect. The spherically scattered matter waves are entangled in such way that every atom in the left ring is entangled with a counterpart on the right ring, located at the diametrically opposite region.

**Keywords**: ENTANGLEMENT, PAIR SOURCE, BELL STATE, QUBIT, QUANTUM METROLOGY, ULTRACOLD ATOMS

## References

[1] R.I. Khakimov, et al. Nature **540**, 100 (2016)

[2] S.S. Hodgman, et al. Phys. Rev. Lett. **118**, 240402 (2017)