A two-particle, four-mode interferometer for atoms

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The extraordinary character of entanglement stems from the fact that the many-body wave-function of entangled particles cannot be factorized in a product of single-particle wave-functions. When one insists on describing such wave-function in our ordinary space-time, one has to face the problem of non-locality. This is clearly evidenced by the violation of Bell's inequalities, which apply to any system that can be described in the spirit of the local realist world view of Einstein, in which physical reality lies in our ordinary space-time. While the violation of Bell's inequalities is a two-particle interference effect, the converse is not true: not all two-particle interferences can lead to a violation of Bell's inequalities, and thus be impossible to describe in a local realist point of view. This is for instance the case of the Hong–Ou–Mandel effect. The key difference between these effects is the number of modes that are made to interfere. While the Hong–Ou–Mandel effect involves only two modes for two particles, a test of Bell's inequalities requires four modes that can be made to interfere two by two at two different places. Experimental tests of Bell's inequalities always closer to the ideal configuration have been performed with low energy photons, or internal states of atoms. But we do not know of experiments on two-particle, four mode interferences involving the external degrees of freedom of massive particles (position or momentum), in a configuration permitting Bell's inequalities to be tested. Such tests involving mechanical observables are desirable, in particular because they may give access to the interface between quantum mechanics and gravitation. In this talk, we propose an experiment enabling the observation of a two-particle, four-mode interference with atoms entangled in momentum, and realize a test of Bell's inequalities. It is based on the experimental set-up used in our recent atomic Hong–Ou–Mandel experiment [1]. We also present preliminary data, recorded with a simplified version of the interferometer, that are are compatible with the existence of a quantum interference in this set-up.

[1] R. Lopes, A. Imanaliev, A. Aspect, M. Cheneau, D. Boiron, and C. I. Westbrook, Nature 520, 66 (2015)