Creating EPR-entangled matter beams

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One of the most fundamental properties of quantum mechanics is non-locality. Although this property has been confirmed in ever more rigorous experiments, all such experiments have used photons, and never massive particles. Such a test is one of the holy grails of quantum atom optics. We have now identified a system and an experimental scheme which exhibits EPR entanglement between matter beams, the essential resource required for such a test.

The first hints came in a metastable helium (He^*) atom laser experiment conducted by a group at the Australian National University. They coupled trapped atoms in a Bose-Einstein condensate (BEC) into an untrapped state, allowing them to form an atom laser and fall under gravity onto a detector which imaged the profile of the beam. At high coupling powers anomalous "peaks" were seen, well seperated from the expected atom laser profile. In simulations where the coupling was on resonance, only full quantum field theory simulations showed the peaks; semiclassical Gross-Pitaevskii simulations did not. This suggested there was a spontaneous vacuum seeding effect taking place. The mechanics of the process are shown in Fig. 1. An exotic form of four wave mixing occurs, with stationary trapped and untrapped atoms colliding and scattering into two beams along the long axis of the BEC.

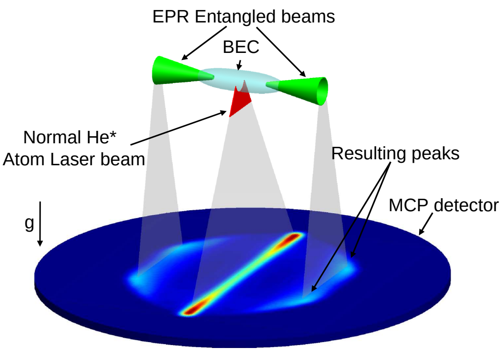

Fig. 1: Outcoupling an atom laser from a BEC with nonlinearity mismatches results in paired matter beams which can be EPR entangled.

While this appears to violate energy conservation, it is allowed due to the peculiar nonlinear energy terms in the He^* system. For details see Dall *et al.* [1]. To investigate whether the twin beams were EPR entangled, we carried out a Bogoliubov analysis of the system. The mean fields which we linearized around were time-dependent, which would normally require a numerical solution, but we managed to prove that the mean fields were periodic, allowing us to apply a novel Floquet approach to gain analytic insight. We demonstrated that there are dynamic instabilities in the BEC which lead to exponential growth of fluctuations that couple opposite momenta. A high aspect-ratio BEC ensures that this amplification can only take place along the long axis of the condensate, leading to directed beams.

We showed that the evolution of the fluctuation operators for the two modes in the system were

$$\begin{aligned}\hat{\Lambda}(\mathbf{k},t) &= e^{i\omega(\mathbf{k})t}\left(\sinh(\gamma(\mathbf{k})t)\hat{\Lambda}'^{\dagger}(-\mathbf{k},0)+\cosh(\gamma(\mathbf{k})t)\hat{\Lambda}(\mathbf{k},0)\right),\\ \hat{\Lambda}'(\mathbf{k},t) &= e^{-i\omega(\mathbf{k})t}\left(\sinh(\gamma(\mathbf{k})t)\hat{\Lambda}^{\dagger}(-\mathbf{k},0)+\cosh(\gamma(\mathbf{k})t)\hat{\Lambda}'(\mathbf{k},0)\right),\end{aligned}$$

identical to degenerate parametric down conversion in optics. Just as PDC is a source of EPR-entangled photon pairs, the beams in our system are EPR-entangled atoms.

The manuscript describing these results in currently in preparation.

References

[1] R. G. Dall, L. J. Byron, A. G. Truscott, G. R. Dennis, M. T. Johnsson, and J. J. Hope, J. Phys. A **79**, 011601R (2009).