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Entangled states of spin and clock oscillators

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Measurements of one quadrature of an oscillator with precision beyond its vacuum state uncertainty have occupied a central place in quantum physics for decades. We have recently reported the first experimental implementation of such measurement with a magnetic oscillator [1]. However, a much more intriguing goal is to trace an oscillator trajectory with the precision beyond the vacuum state uncertainty in *both* position and momentum, a feat naively assumed not possible due to the Heisenberg uncertainty principle. We have demonstrated that such measurement is possible if the oscillator is entangled with a quantum reference oscillator with an effective negative mass [2,3]. The key element is the cancellation of the back action of the measurement on the composite system of two oscillators. Applications include measurements of e.-m. fields, accelleration, force and time [4] with practically unlimited accuracy. In a more general sense, this approach leads to trajectories without quantum uncertainties and to achieving new fundamental bounds on the measurement precision.

1. G. Vasilakis et al. *Nature Phys.*, (2015) doi:10.1038/nphys3280.

2. K. Hammerer et al. *Phys. Rev. Lett.* 102, 020501 (2009).

3. E.S. Polzik and K.Hammerer. *Annalen der Physyk*. 527, No. 1–2, A15–A20 (2015).

4. E. S. Polzik and J. Ye. doi: 10.1103/PhysRevA.93.021404 (2016).