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Quantum back action free measurement of motion in a negative mass reference frame

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It has been proposed [1-3] that a measurement of motion with precision beyond the vacuum state uncertainty in both position and momentum is possible if it is carried out in a quantum reference frame with an effective negative mass. In such a measurement, the quantum back action is evaded due to the destructive interference of the back action on the object and on the reference frame. The reference frame can be implemented with an oscillator which has its first excited state energy below the ground state energy, such for an atomic spin oscillator oriented along the magnetic field [4]. We report on the experiment where the motion of the oscillator is tracked in the reference frame of the spin oscillator by probing this hybrid quantum system with light. The mechanical oscillator is a macroscopic millimeter size membrane [6]. The atomic oscillator is a long lived collective spin of an atomic ensemble [4]. We demonstrate the evasion of the quantum back action of the measurement in the hybrid system and study an intricate interplay between quantum back action and the opto-mechanical cooling force. The negative mass reference frame physics opens the way towards generation of entanglement between the mechanical oscillator and an atomic spin, leading to applications in fundamental physics of entangled macroscopic objects, and force, gravitation and acceleration measurements beyond standard quantum limits. [1] K. Hammerer, M. Aspelmeyer, E.S. Polzik, P. Zoller. *Phys. Rev. Lett.* 102, 020501 (2009). [2] E.S. Polzik and K.Hammerer. *Annalen der Physyk*. 527, No. 1–2, A15–A20 (2015). [3] M. Tsang and C. Caves, *Phys. Rev. Lett.* 105(12), (2010). [4] G. Vasilakis et al. Nature Physics, doi:10.1038/nphys3280 (2015). [5] C. Møller, R. Thomas, G. Vasilakis, E. Zeuthen, Y. Tsaturyan, K. Jensen, A. Schliesser, K. Hammerer and E.S. Polzik. Manuscript in preparation. [6] Y. Tsaturyan et al. Optics Express, Vol. 22, Issue 6, pp. 6810-6821 (2014).