Quantum Enhanced Microrheology of a Living Cell

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Abstract

We demonstrate the first biological measurement with precision surpassing the quantum noise limit. Lipid particles within a living yeast cell are tracked with sub-shot noise sensitivity, thereby revealing the biological dynamics of the cellular cytoplasm.

I. INTRODUCTION

Quantum metrology allows high sensitivity measurements to proceed with a lower light intensity than classically possible [1]. A particularly important frontier for this technology is in biological measurements, where photochemical interactions often disturb biological processes and can damage the specimen [2]. Here we report the first demonstration of biological measurement with precision surpassing the quantum noise limit [3]. We used amplitude squeezed light to perform microrheology experiments within Saccharomyces cerevisiae yeast cells with precision surpassing the quantum noise limit by 42%. This entailed tracking the thermal motion of naturally occurring lipid granules, which is determined by the mechanical properties of the surrounding cytoplasm and the embedded polymer networks. From this motion the viscoelastic moduli of the surrounding cytoplasm could be determined in real time, with squeezed light allowing a 64% higher measurement rate than possible classically, improving the temporal resolution of the biological dynamics of the cellular cytoplasm [5]. The approach presented here is widely applicable, extending the reach of quantum enhanced measurement to many dynamic biological processes. Furthermore, by demonstrating that biological measurements can be improved using quantum correlated light, our results pave the way to a broad range of applications in areas such as two-photon microscopy, super-resolution, and absorption imaging [1].

II. PARTICLE TRACKING METHOD

To enable the reported results, we developed a new laser based microscopy system which extended previous methods used to track the motion of highly reflective mirrors with non-classical light to measurements of microscopic particles with non-paraxial fields (shown in Fig. 1). This is an optical tweezers setup with a number of significant modifications. Firstly, dark-field illumination is used [6], which intrinsically causes only side-scattered light to enter the measurement. Because large objects predominantly scatter light forward, this feature ensures that when measuring motion in yeast cells, most of the captured light has scattered from a lipid granule. Secondly, this illumination is stroboscopically pulsed, allowing an optical lock-in measurement which made biological dynamics in the critical Hz-kHz frequency range accessible. This straightforward technique allowed quantum enhancement over a frequency range which reached as low as the range reported for squeezed light sources developed for gravity wave interferometers [4], without changing the quantum limit on sensitivity [7]. Thirdly, a self-homodyne measurement was performed, with the position extracted from interference between a shaped local oscillator field and scattered light rather than by using the conventional quadrant detector. This allowed the local oscillator field shape to be optimized independently of the probe or trapping fields, and when amplitude squeezed, any spatial mode perturbations occurring during optical propagation were applied equally to both the squeezing and local oscillator, ensuring perfect overlap at detection.

![Image](Layout of the particle tracking experiment. Counter-propagating trap fields (yellow) confined the particles, and are isolated from the detection with polarizing beamsplitters (PBS). A separate probe field illuminates the particles, and scattered light from this mixes with a local oscillator to reveal particle position. A separate green field is also used to image the particles onto a CCD camera.)

With this apparatus, we tracked 2 μm diameter silica beads in water, and confirmed that we could measure Brownian motion with the lock-in technique (Fig. 2 a, b). With squeezed light, we could enhance the sensitivity by up to 2.7 dB (Fig. 2 c).

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motion is termed subdiffusive. (1301.5975) The first biological measurement beyond the quantum limit was achieved through squeezed light which improved measurement precision. The work was supported by the Australian Research Council Discovery Project Contract No. DP0985078.

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