Supplemental Material: Proposal for an optomechanical Bell test

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PART I

In the general case where the mechanical oscillator is not in its ground state but in a thermal state with n_0 excitations, the joint probability given in Eq. (9) of the main text becomes

$$P(+1+1|\alpha_1\alpha_2) = \frac{(1-p)}{\eta' n_0 - (\eta'-1)p(\eta+\eta n_0 - 1)+1}$$
$$\times e^{-\frac{\eta|\alpha_1|^2(\eta' n_0+(\eta'-1)p+1)+\eta' T|\alpha_2|^2(p(\eta+\eta n_0-1)+1)}{\eta' n_0-(\eta'-1)p(\eta+\eta n_0-1)+1}}$$
$$\times e^{-\frac{\sqrt{p}\eta\eta'(n_0+1)\sqrt{T}(\alpha_1^*\alpha_2^*+\alpha_1\alpha_2)}{\eta' n_0-(\eta'-1)p(\eta+\eta n n_0-1)+1}}.$$

Similarly for the marginals

$$P(+1|\alpha_1) = (1-p)\frac{e^{-\frac{\eta(1-p)|\alpha_1|^2}{(\eta+\eta n_0-1)p+1}}}{p(\eta+\eta n_0-1)+1},$$

and

$$P(+1|\alpha_2) = (1-p)\frac{e^{-\frac{\eta'(1-p)|\alpha_2|^2 T}{(\eta' n_0+(\eta'-1)p+1)}}}{\eta' n_0+(\eta'-1)p+1}.$$

PART II

We here briefly discuss how the locality-loophole can be closed in our proposal. This requires two detectors as show in Fig. 1. The first photon that is obtained by driving the mechanics with the blue detuned laser is sent to Bob's location while the correlated phonon is stored in the mechanics. Once the photon is close to Bob's location, the phonon is converted into a photon (via the red detuned laser) which is detected locally, at Alice's location. If Bob's lab is space-like separated from Alice's location, the locality loophole is closed through the no-signaling principle. This takes a few hundred meters as shown e.g. in Ref. [1], i.e. it entails only negligible losses at 1550 nm and storage times of the order of 1 μs which is achievable with the system proposed in the feasibility study [2]. Together with high efficiency detections, this provides a clear recipe for a loophole-free Bell test.

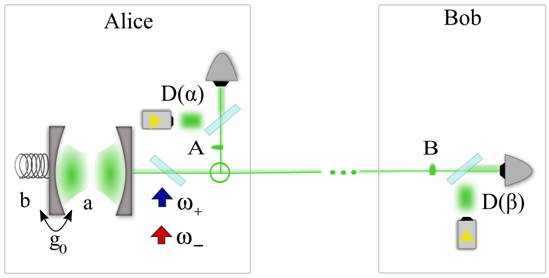

FIG. 1: Extension of the scheme presented in Fig. 1 A) in the main text to close the locality loophole.

We emphasize that the aim of our proposal is not only to perform a loophole-free Bell test. Even in the simplest configuration with one detector only (as shown in Fig. 1 A) of the main text), the violation of the CHSH-Bell inequality would show non-classical correlations between light and mechanics that are stronger than entanglement, i.e. non-local correlations (see e.g. [3] for examples of states that are entangled which do not violate a Bell inequality, i.e. leading to correlations that can be reproduced by local strategies). Furthermore, as is the case for any-Bell test, this conclusion holds device-independently, without assumptions on the dimension of the underlying Hilbert space or on the precise alignement of the measurement settings [4]. Hence, our results open the way for device-independent quantum information processing [5] with optomechanical systems, where space-like separation is not required.

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