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Controlling two-photon interference and entanglement with mechanical rotations

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ABSTRACT

We review recent experimental and theoretical results of photon interferometry on rotating platforms. Quantum phenomena such as two-photon interference and entanglement can be controlled with mechanical rotations in a regime accessible to table-top experiments. We first discuss experiments demonstrating how low-frequency mechanical rotations affect the bunching behavior of frequency-entangled photon pairs. It was shown that low-frequency mechanical rotations can affect the temporal distinguishability of photons and can transform photonic behavior from perfectly indistinguishable (bosonic behavior) to perfectly distinguishable (fermionic behavior). We then give a future outlook for testing the generation of entanglement from mechanical rotation. A recent theoretical work showed that generating path-polarization entanglement from mechanical rotations could be verified with present technology. These works make a strong case for further exploration of quantum phenomena at the interface with non-inertial (rotational) motion.

Keywords: Sagnac effect, Rotating reference frame, Non inertial motion, Quantum Foundations, Low frequency mechanical rotations, Bunching statistics, Photonic entanglement

1. INTRODUCTION

The seminal works by Sagnac[1, 2] have led to a new operational way to measure rotational motion using optical fields. Using refinements of the same basic principle Michelson measured the daily rotation of the Earth,[3] and the current state-of-the-art with ring laser gyroscopes can achieve exquisite sensitivities of angular frequencies.[4] Several Sagnac matter-wave interferometry experiments[5] have also been performed with superconducting electrons,[6] neutrons[7] and atoms.[8–10] General reviews of the Sagnac effect can be found in.[11–14]

Photonic technologies have in the last decades also allowed the exploration of the coupling between quantum states of light and mechanical rotations. The demonstration of the single-photon Sagnac interferometer[15] was followed by a series of two-photon experiments. Polarization-entangled photon pairs were shown to remain unaffected when placed on a centrifuge.[16] A Sagnac phase shift on a two-photon NOON state was observed in,[17] and the current sensitivities allow the measurement of the Earth's daily rotation.[18]

Here we review how mechanical rotations affect photon bunching in a Hong-Ou-Mandel (HOM) setup. It was shown that the temporal distinguishability of photons is affected by low-frequency mechanical rotations resulting in a shift of the HOM dip.[19] Furthermore, mechanical rotations can transform photonic behavior from perfectly indistinguishable (bosonic behavior) to perfectly distinguishable (fermionic behavior) changing HOM dips into peaks[20] (see also[21] where the effect was first suggested theoretically). We then give a brief outlook for testing the generation of entanglement from mechanical rotation. We discuss a recently proposed scheme for generating path-polarization entanglement at low frequencies of rotation using an experimentally accessible platform.[22]

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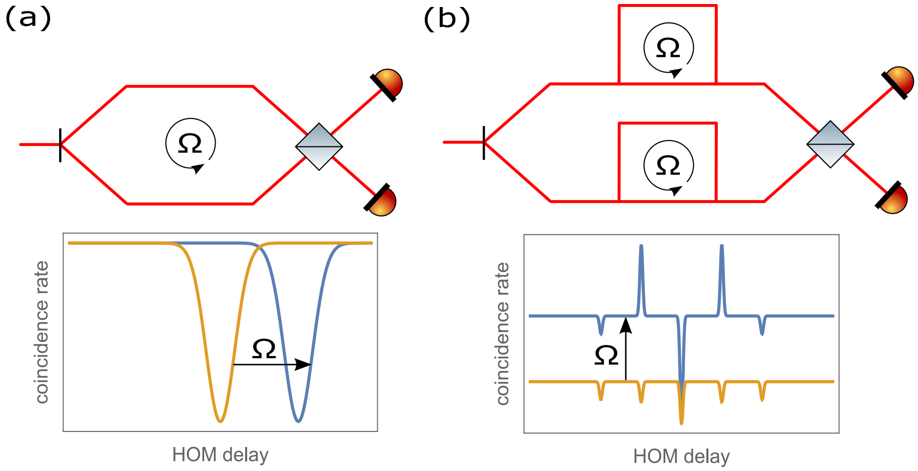

Figure 1. In the top row we give blueprints of experiments with frequency-entangled photon pairs on rotating platforms, and in the bottom row we illustrate the effect of mechanical rotations on the photon bunching statistics. (a) Hong-Ou-Mandel scheme on a rotating platform.[19] The effect of mechanical rotations is to shift the HOM dip left or right depending on the direction of rotation. (b) Hong-Ou-Mandel scheme on a rotating platform with nested loops added to the arms of the interferometer.[20, 21] By changing the angular frequency two HOM dips change into HOM peaks. By further increasing the angular frequency we observe transitions between dips to peaks periodically. We observe a similar behavior also when changing the direction of rotation.

2. BUNCHING AND ANTIBUNCHING IN ROTATING REFERENCE FRAMES

We review the two-photon interferometry experiments depicted in Fig. 1. The experimental signature is given by the probability of coincidence detection:

$$P^{(2)}(\delta t,\Omega)=\int dt_1\int dt_2\langle\psi_f|\hat{b}^\dagger(t_1)\hat{a}^\dagger(t_2)\hat{a}(t_2)\hat{b}(t_1)|\psi_f\rangle, \tag{1}$$

where δt is the HOM delay (controllable by the experimentalist), Ω is the angular frequency of the rotating platform, $\hat{a}$, $\hat{b}$ are the two output modes, and $|\psi_f\rangle$ is the final two-photon state. For the special case $\Omega=0$ the coincidence probability $P^{(2)}(\delta t,0)$ reduces to the case without mechanical rotations.

As illustrated in Fig. 1 (a) and (b), the experiments demonstrated that the coincidence probability $P^{(2)}(\delta t,\Omega)$ changes as a function of the angular frequency Ω. Fig. 1 (a) illustrates how a mechanical rotation induces a shift of the HOM dip. It was found that the shift of the HOM dip matches the Sagnac delay given by:[11]

$$t_s(\Omega)=\frac{4A\Omega}{c^2}, \tag{2}$$

where A is the effective area of the interferometric loop, and c is the speed of light. Fig. 1 (b) depicts how the mechanical rotations transform HOM dips into HOM peaks. The switch from dips (the case without rotation) to peaks occurs when the accumulated phase difference is $\omega t_s=\pi$, where ω is the mean frequency of the photon, and t_s is the accumulated Sagnac delay given in Eq. (2).

3. GENERATION OF ENTANGLEMENT FROM MECHANICAL ROTATION

We conclude with a brief discussion about the future outlook for generating entanglement from mechanical rotations. A recent theoretical analysis suggested that an initially separable path-polarization state of a single photon could become maximally entangled from mechanical rotations.[22] For the proposed schemes it was found that the generated concurrence C, quantifying the degree of entanglement,[23] would scale as

$$C=|\sin(\omega t_s)|, \tag{3}$$

where t_s is the Sagnac delay given in Eq. (2) (with A the effective interferometric area), and ω is the photon's frequency. When we have $\Omega=0$ we find $\omega t_s=0$ and hence $C=0$, which indicates that no entanglement would be generated (case without rotation). However, when the angular frequency Ω is tuned to achieve $\omega t_s = \pi/2$ we find $C = 1$, which suggests that maximal entanglement would be generated in the experiment. The path-polarization entanglement could then be transferred to a two-photon state using entanglement swapping protocols.[24,25]

4. SUMMARY

At the practical level, the experimental control of quantum phenomena using mechanical rotations could find applications for quantum sensing, communication and computing.[26] At the fundamental level, explorations of non-inertial (rotational) motion using quantum states of light could shed light on the elusive relation between quantum theory and gravity.[22] Quoting Albert Einstein on the origin of non-inertial (rotational) phenomena: "... there is a gravitational field (field of centrifugal force, and force of Coriolis)...".[27] In summary, the discussed works, experimental and theoretical, suggest further exploration of the relation between mechanical rotations and quantum phenomena.

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