Quantum Optics, Homework 2

Jinyuan Wu

November 6, 2021

Details in the HBT experiment Figure 1 shows an experimental validation of the HBT effect. (a) Describe the expected phenomenon the experiment. Compare the expected phenomenon with the original HBT effect in astronomical observation. (b) Explain the phenomenon within classical electrodynamics. (c) Point out why the classical explanation is not enough. Construct a simplified version of the experiment and explain it with quantum optics.

Solution

(a) The integrating motor gives the averaged intensity correlation function, i.e.

$$\langle I_1 I_2 \rangle := \lim_{T\to\infty} \frac{1}{T} \int_0^T \mathrm{d}t\, I_1(t) I_2(t). \tag{1}$$

The expected results include that

$$\langle I_1 I_2 \rangle - \langle I_1 \rangle \langle I_2 \rangle \neq 0, \quad g^{(2)} > 1, \tag{2}$$

and that the intensity fluctuation correlation function

$$\langle \Delta I_1 \Delta I_2 \rangle = \langle I_1 I_2 \rangle - \langle I_1 \rangle \langle I_2 \rangle \tag{3}$$

reaches its peak when the optical path difference of the two beams is zero, and then drops away as the separation between the two beams increases. If the light source is laser, the relation between $g^{(2)}$ and the optical path difference is in the form of $1 + A\cos(k\Delta r)$, while if the light source is thermal - as is the case of a mercury arc - the relation between $g^{(2)}$ and the optical path separation is something like Figure 2.

(b) Suppose the electric field before the beam splitter is $E(t)\cos(\omega t)$, where the characteristic frequency of $E(t)$ is much smaller than ω. The beam splitter introduces a phase difference of π between the reflected beam and the transmitted beam, and the fact that MO_1 may be different with MO_2 introduces another phase difference. The electric fields at detecter 1 and detecter 2 are therefore

$$E_1 = E(t-\tau_1)\cos(\omega(t-\tau_1)), \quad E_2 = E(t-\tau_2)\cos(\omega(t-\tau_2)), \tag{4}$$

respectively. The intensities of E_1 and E_2 are

$$I_1(t) = \overline{E(t-\tau_1)^2 \cos^2 \omega(t-\tau_1)} = \frac{1}{2}E(t-\tau_1)^2, \quad I_2(t) = \frac{1}{2}E(t-\tau_2)^2. \tag{5}$$

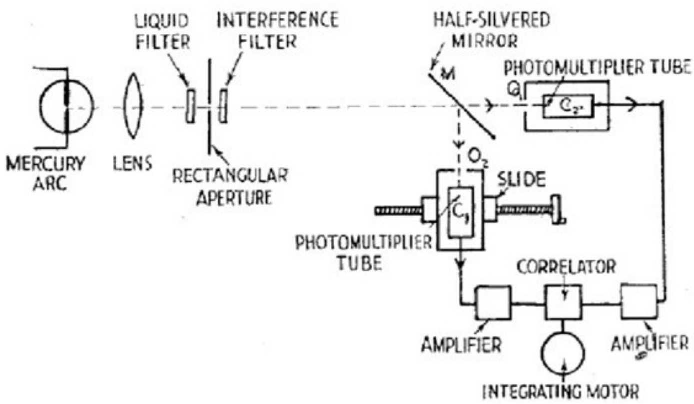

Figure 1: HBT effect in laboratory

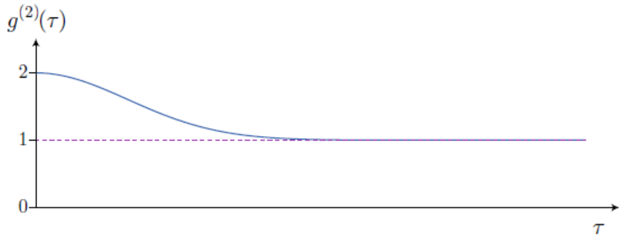

Figure 2: Second order coherence with a thermal light source in Gaussian distribution (figure taken from [1], Section 2.6.1). The maximum of $g^{(2)}$ is 2, which is a result of the optical field obeying a Gaussian distribution, where the Wick theorem holds so $\langle E_1^* E_2^* E_3 E_4 \rangle = \langle E_1^* E_3 \rangle \langle E_2^* E_4 \rangle + \langle E_1^* E_4 \rangle \langle E_2^* E_3 \rangle$, and hence $\langle I^2 \rangle = 2 \langle I \rangle^2$.

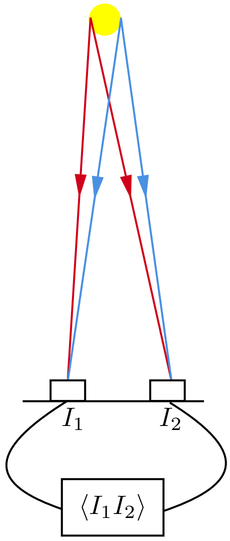

Figure 3: HBT in astronomical observation

The correlation function is therefore

$$\langle I_1 I_2 \rangle = \langle I_1(t) I_2(t) \rangle = \frac{1}{4} \langle E(t-\tau_1)^2 E(t-\tau_2)^2 \rangle . \tag{6}$$

With a thermal light source, when $|\tau_1 - \tau_2|$ is large, $E(t-\tau_1)$ and $E(t-\tau_2)$ is not correlated, and we have

$$g^{(2)} = \frac{\langle I_1 I_2 \rangle}{\langle I_1 \rangle \langle I_2 \rangle} \approx \frac{\langle I_1 \rangle \langle I_2 \rangle}{\langle I_1 \rangle \langle I_2 \rangle} = 1.$$

When $\tau_1 = \tau_2$, however, we have

$$\langle (I_1(t) - \langle I_1 \rangle)(I_2(t) - \langle I_2 \rangle) \rangle > 0,$$

and subsequently

$$\langle I_1 I_2 \rangle - \langle I_1 \rangle \langle I_2 \rangle > 0,$$

so $g^{(2)} > 1$. So we have something like Figure 2.

(c) When the classical picture of the optical field fails, the classical explanation fails as well. For example, when the light source creates a sequence of single-photon pulses, what will be observed is *photon antibunching* where $g^{(2)} = 0$ instead of bunching, because one photon cannot appear at two sites.

Conditional generation of single photon pulses Many research and applications in quantum optics needs single photon pulses, that is, a wave packet of light that contains exactly one single photon. Such a single photon pulse can be generated in two ways: The deterministic approach via single atom emission, and the so-called heralded approach. This problem discusses a simplified version of the later. Consider a bi-photon generation process described by the Hamiltonian

$$H = \beta a_k^\dagger b_{k'}^\dagger + \text{h.c.}. \tag{7}$$

Here $a_k^\dagger, b_{k'}^\dagger$ are creation operators of photons into the k, k' propagation modes respectively. Such process can be realized for example in a frequency down conversion experiment, where a single photon is "split" into two in a nonlinear optical crystal, or a 4-wave mixing experiment where two incoming photons are converted into two output photons in an atomic gas. (a) Consider initially light is in vacuum state $|\psi(0)\rangle = |V\rangle$. Consider that the bi-photon generation process is switched on for time τ and then off, with $\xi = \beta\tau \ll 1$. Integrate the Schrodinger equation to obtain $|\psi(\tau)\rangle$, that is, the photon state after the interaction. (b) Consider a photon detector positioned L meters away from the bi-photon generation device along the k' propagation pathway. The time interval that the detector can detect a $b_{k'}$ photon is $[L/c, L/c+\tau]$ (we ignore any change of light speed within the experiment). For an ideal photon detector, what is the probability of detecting 1 photon, and detecting 2 photons during this time interval? If one photon is detected along k', what is the photon state in the k path? The strategy is the so called heralded single photon generation: a nearly perfect single photon pulse in the k mode is heralded by the detection of a single photon in the k'-mode.

Solution

(a) In the interaction picture, the time evolution of the state is given by

$$\mathrm{i}\frac{\mathrm{d}}{\mathrm{d}t}|\psi(t)\rangle = H|\psi(t)\rangle = h(t)\left(\beta a_k^\dagger b_{k'}^\dagger + \text{h.c.}\right)|\psi(t)\rangle\,,$$

where $h(t)$ is one when $t \in [0, \tau]$ and zero otherwise. Formally we have

$$|\psi(t)\rangle = \mathcal{T}\exp\left(-\mathrm{i}\int_0^t \mathrm{d}t'\, h(t')(\beta a_k^\dagger b_{k'}^\dagger + \text{h.c.})\right)|\psi(0)\rangle\,.$$

Since $\xi \ll 1$, the operators approximately do not have time evolution, and thus we have

$$\begin{aligned} |\psi(\tau)\rangle &= \exp\left(-\mathrm{i}\tau(\beta a_k^\dagger b_{k'}^\dagger + \text{h.c.})\right)|\psi(0)\rangle \\ &= \mathrm{e}^{-\mathrm{i}\xi(a_k^\dagger b_{k'}^\dagger + a_k b_{k'})}|0\rangle\,. \end{aligned} \tag{8}$$

(b) Since the time interval is very short, we can view the measurement as simply measuring the state (8) as the pulse comes across the detector. Expanding (8) we have

$$\begin{aligned} |\psi(\tau)\rangle =& \ |0\rangle - \mathrm{i}\xi(a_k^\dagger b_{k'}^\dagger + \text{h.c.})|0\rangle + \frac{1}{2}(-\mathrm{i}\xi)^2(a_k^\dagger b_{k'}^\dagger + \text{h.c.})^2|0\rangle + \cdots \\ =& \left(1 - \frac{\xi^2}{2} + \cdots\right)|0\rangle - (\mathrm{i}\xi + \cdots)|n_k = 1, n_{k'} = 1\rangle - \left(\frac{1}{2}\xi^2 + \cdots\right)|n_k = 2, n_{k'} = 2\rangle + \cdots. \end{aligned}$$

Taking only the leading order terms, we have

$$P(n_k = 1) = \xi^2, \quad P(n_k = 2) = \frac{\xi^4}{4}. \tag{9}$$

It can be seen that in $|\psi(\tau)\rangle$ we always have $n_k = n_{k'}$, and therefore if one photon is detected along k', the photon state in the k path is $|n_k = 1\rangle$. Therefore if we placed a baffle in path k, which is removed when $n_{k'}$ is detected to be 1, whenever a pulse is generated, it is a single-photon one.

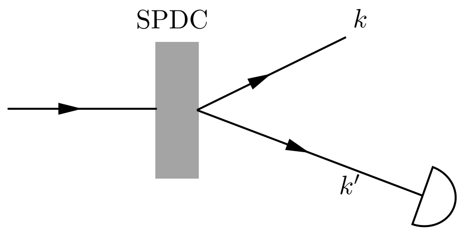

Figure 4: Light circuit in the heralded approach

Details in the NLS process Analyze the NLS process in detail. The circuit is shown in Figure 5, and the two beam splitters are represented as

$$S_1 = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}, \quad S_2 = \begin{pmatrix} \cos\sigma & \sin\sigma \\ -\sin\sigma & \cos\sigma \end{pmatrix} \tag{10}$$

(a) Derive the output quantum state before the measurement. (b) Find the conditional quantum state with the measurement results shown in Figure 5. (c) Find when the NLS process works in terms of θ and σ, and the probability of a successful NLS.

Solution

(a) The optical circuit is linear its transformation matrix is

$$S = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\sigma & \sin\sigma \\ 0 & -\sin\sigma & \cos\sigma \end{pmatrix} \begin{pmatrix} \cos\theta & \sin\theta & 0 \\ -\sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta & 0 \\ -\cos\sigma\sin\theta & \cos\sigma\cos\theta & \sin\sigma \\ \sin\theta\sin\sigma & -\cos\theta\sin\sigma & \cos\sigma \end{pmatrix}, \tag{11}$$

and we have

$$b_j^\dagger = S_{jk} a_k^\dagger. \tag{12}$$

The quantum state is

$$|\psi\rangle = \big(\alpha + \beta a_1^\dagger + \frac{\gamma}{\sqrt{2}}(a_1^\dagger)^2\big) a_2^\dagger |0\rangle .$$

By (11) and (12) we have

$$[a_i]^\dagger = \begin{pmatrix} \cos\theta & -\cos\sigma\sin\theta & \sin\theta\sin\sigma \\ \sin\theta & \cos\theta\cos\sigma & -\cos\theta\sin\sigma \\ 0 & \sin\sigma & \cos\sigma \end{pmatrix} [b_i^\dagger],$$

and therefore we have

$$\begin{aligned} |\psi\rangle = \Big(&\alpha + \beta(b_1^\dagger\cos\theta - b_2^\dagger\sin\theta\cos\sigma + b_3^\dagger\sin\theta\sin\sigma) \\ &+ \frac{\gamma}{\sqrt{2}}(b_1^\dagger\cos\theta - b_2^\dagger\sin\theta\cos\sigma + b_3^\dagger\sin\theta\sin\sigma)^2\Big) \\ &\times (b_1^\dagger\sin\theta + b_2^\dagger\cos\theta\cos\sigma - b_3^\dagger\cos\theta\sin\sigma)|0\rangle . \end{aligned} \tag{13}$$

(b) In (13), the $b_1^\dagger(b_2^\dagger)^0$ terms are

$$\begin{aligned} &\alpha b_1^\dagger\sin\theta + \beta b_1^\dagger\cos\theta \times (-b_3^\dagger\cos\theta\sin\sigma) \\ &+ \beta b_3^\dagger\sin\theta\sin\sigma \times b_1^\dagger\sin\theta \\ &+ \frac{2\gamma}{\sqrt{2}} b_1^\dagger\cos\theta \times b_3^\dagger\sin\theta\sin\sigma \times (-b_3^\dagger\cos\theta\sin\sigma) \\ &+ \frac{\gamma}{\sqrt{2}}(b_3^\dagger)^\dagger\sin^2\theta\sin^2\sigma \times b_1^\dagger\sin\theta, \end{aligned}$$

which also reads

$$(\alpha\sin\theta + b_3^\dagger\beta\sin\sigma\cos 2\theta + \frac{1}{\sqrt{2}}(b_3^\dagger)^2\gamma(\sin^2\theta - 2\cos^2\theta)\sin\theta\sin^2\sigma)b_1,$$

and therefore the conditional quantum state is

$$|\psi\rangle_{\text{cond-out}} = \alpha \sin\theta\,|1,0,0\rangle + \beta \sin\sigma \cos 2\theta\,|1,0,1\rangle + \gamma(\sin^2\theta - 2\cos^2\theta)\sin\theta \sin^2\sigma\,|1,0,2\rangle\,. \tag{14}$$

Note that the state is *not* normalized. Its norm gives the probability to obtain such a state.

(c) The output state of a NLS process is

$$\alpha\,|0\rangle + \beta\,|1\rangle - \gamma\,|2\rangle\,.$$

(14) satisfied this condition if and only if

$$\sin\sigma\cos 2\theta = \sin\theta, \quad (\sin^2\theta - 2\cos^2\theta)\sin\theta\sin^2\sigma = -\sin\theta.$$

Eliminating σ we have

$$(2\cos^2\theta - \sin^2\theta)\frac{\sin^2\theta}{\cos^2 2\theta} = 1,$$

from which we find

$$\sin^2\theta = \frac{3 \pm \sqrt{2}}{7}.$$

Since

$$2\cos^2\theta - \sin^2\theta > 0,$$

we throw away solution and only keep the solution $(3-\sqrt{2})/7$. Note that $\cos 2\theta > 0$, so the sign of $\sin\theta$ and σ is the same, and if we add a negative sign to both θ and σ we just get another solution. This is correct because the phase of (14) cannot be determined uniquely. Without loss of generality we take

$$\sin\theta = \sqrt{\frac{3-\sqrt{2}}{7}},$$

and hence

$$\sin\sigma = \frac{\sin\theta}{\cos 2\theta} = \frac{\sin\theta}{1 - 2\sin^2\theta} = \frac{\sqrt{21 - 7\sqrt{2}}}{1 + 2\sqrt{2}}.$$

So

$$\theta = \arcsin\sqrt{\frac{3-\sqrt{2}}{7}} = 28.42^\circ, \quad \sigma = \arcsin\frac{\sqrt{21-7\sqrt{2}}}{1+2\sqrt{2}} = 60.49^\circ. \tag{15}$$

Of course,

$$\theta = 180^\circ - 28.42^\circ = 151.58^\circ, \quad \sigma = 180^\circ - 60.49^\circ = 119.51^\circ. \tag{16}$$

When NLS is possible, we have

$$|\psi\rangle_{\text{cond-out}} = \alpha\sin\theta\,|1,0,0\rangle + \beta\sin\theta\,|1,0,1\rangle - \gamma\sin\theta\,|1,0,2\rangle\,.$$

The successful probability is the square of the norm, which is

$$P_{\text{succ}} = \sin^2\theta = \frac{3-\sqrt{2}}{7} = 22.65\,\%. \tag{17}$$

The $1/f$ noise
Solution

Laser phase-locking
Solution

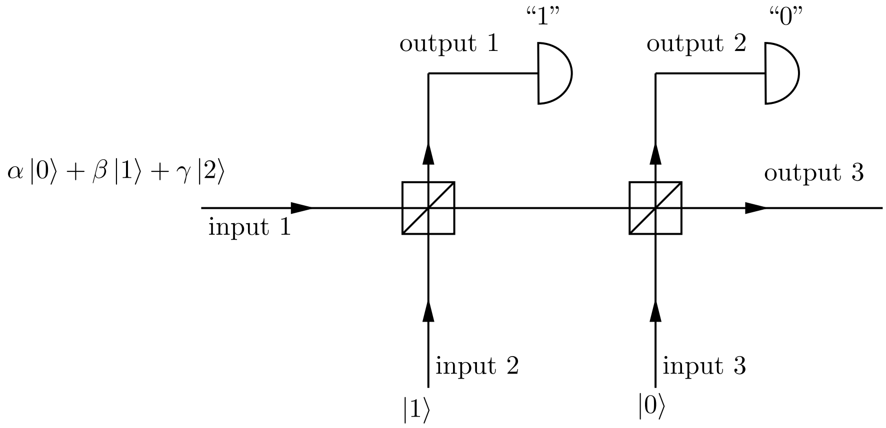

Figure 5: The NLS circuit

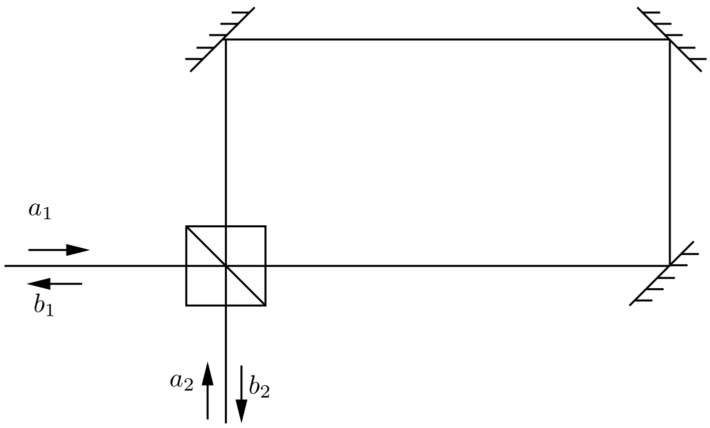

Figure 6: The Sagnac interferometer

Measuring earth rotation with a Sagnac interferometer In a Sagnac interferometer (see Figure 6), input modes a_1, a_2 are mixed by a 50% - 50% beam splitter S, with its outputs follow "time-reversal" pathways of each other so as to be "re-mixed" by the same beam splitter S into b_1 and b_2 modes. (a) Express the linear transformation matrix that couples the input a_1, a_2 and output b_1, b_2 modes. Try to argue that in absence of rotation, the 2×2 transformation matrix S is diagonal, i.e., when the a_1 port is seeded with a laser and a_2 port is left in vacuum state, then the b_2 output port is a "dark port". (b) It turns out when the interferometer is placed in a rotating frame, such as on earth, the counter-propagating light paths around the loop with area A can pick up a "Sagnac" phase,

$$\varphi_{\rm sagnac} = \frac{4\pi\Omega \cdot A}{c\lambda}$$

Here λ is optical wavelength of the light. In presence of the Sagnac phase, derive the linear transformation matrix S again. (c) Consider a_1 mode is associated with pulsed laser input with duration $\tau = 1\,\text{ms}$. The input states $|\psi_{\rm in}\rangle = {\rm e}^{\alpha a_1^\dagger - \alpha^* a_1}|V\rangle$ is a coherent state in the a_1 mode. For $A = 1\,\text{m}^2$, and let's consider the device is placed at the north pole. Suggest a detection scheme to measure the earth rotation rate (maybe quite difficult, if it is too difficult please allow yourself to be able to "control" the earth rotation). Assuming ideal detection, then how many photons are needed for the interferometer to measure earth rotation rate within 1% accuracy, using a single 1 nm pulse? (e) Provide a detailed argument that the Δn_2 shot noise for the $n_2 = b_2^\dagger b_2$ measurement in this Sagnac interferometer is a result of vacuum fluctuation with $|V\rangle$ enters from the a_2 port to the b_2 port. (f) Provide a plausible experimental arrangement to inject a "squeezed vacuum" into a_2 port, so as to improve the rotation measurement accuracy by a ${\rm e}^{\xi}$ factor.

Solution

(a) The matrix of S is

$$\frac{1}{\sqrt{2}}\begin{pmatrix}1 & -1\\ 1 & 1\end{pmatrix}.$$

Its time reversal is

$$\frac{1}{\sqrt{2}}\begin{pmatrix}1 & 1\\ -1 & 1\end{pmatrix},$$

and after being reflected by all the mirrors beam 1 is at the position of the output port 2 and beam 2 is at the position of the output port 1, so the transformation matrix for the two reflected beams can be obtained by swapping the columns of $S^\dagger$, so the final matrix of the whole system is

$$S_{\text{total}} = \frac{1}{\sqrt{2}}\begin{pmatrix}1 & 1\\ 1 & -1\end{pmatrix}\cdot\frac{1}{\sqrt{2}}\begin{pmatrix}1 & -1\\ 1 & 1\end{pmatrix} = \begin{pmatrix}1 & \\ & -1\end{pmatrix}. \tag{18}$$

The matrix is indeed diagonal, so port b_2 is a dark port without input in a_2 port.

(b) Now the total matrix is

$$\begin{aligned}S_{\text{total}}(\varphi) &= \frac{1}{\sqrt{2}}\begin{pmatrix}1 & 1\\ 1 & -1\end{pmatrix}\cdot\begin{pmatrix}\mathrm{e}^{\mathrm{i}\varphi} & \\ & \mathrm{e}^{-\mathrm{i}\varphi}\end{pmatrix}\cdot\frac{1}{\sqrt{2}}\begin{pmatrix}1 & -1\\ 1 & 1\end{pmatrix}\\ &= \begin{pmatrix}\cos\varphi & -\mathrm{i}\sin\varphi\\ \mathrm{i}\sin\varphi & -\cos\varphi\end{pmatrix},\end{aligned} \tag{19}$$

where φ is the Sagnac phase.

(c) From

$$\begin{pmatrix}b_1^\dagger\\ b_2^\dagger\end{pmatrix} = \begin{pmatrix}\cos\varphi & -\mathrm{i}\sin\varphi\\ \mathrm{i}\sin\varphi & -\cos\varphi\end{pmatrix}\begin{pmatrix}a_1^\dagger\\ a_2^\dagger\end{pmatrix}$$

we find

$$\begin{pmatrix}a_1^\dagger\\ a_2^\dagger\end{pmatrix} = \begin{pmatrix}\cos\varphi & -\mathrm{i}\sin\varphi\\ \mathrm{i}\sin\varphi & -\cos\varphi\end{pmatrix}\begin{pmatrix}b_1^\dagger\\ b_2^\dagger\end{pmatrix}. \tag{20}$$

By substituting

$$a_1^\dagger = \cos\varphi b_1^\dagger - \mathrm{i}\sin\varphi b_2^\dagger$$

into $|\psi_{\text{in}}\rangle$, we obtain

$$|\psi_{\text{out}}\rangle = \mathrm{e}^{\alpha(\cos\varphi b_1^\dagger - \mathrm{i}\sin\varphi b_2^\dagger) - \alpha^*(\cos\varphi b_1 + \mathrm{i}\sin\varphi b_2)}|0\rangle. \tag{21}$$

(e) We need to measure n_2 with (21).

References

[1] Daniel A. Steck. Quantum and atom optics. available online at http://steck.us/teaching, 2020.