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Applications of single photons in quantum metrology, biology and the foundations of quantum physics

In the format provided by the authors and unedited

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1.1 Useful notions for quantum metrology

1.1.1 Shot-noise limit

The notion of photon shot-noise limit (also called Poisson noise) is very important for quantum metrology when dealing with single photon measurement.

We recall that shot-noise is a type of noise following a Poisson process (see section 1.1.1.C of part 1 SI). As photons behave like particles when detected by a single photon detector, shot-noise is relevant for photon counting. Let us consider an experiment with N photons detected. When N is large enough, the Poisson statistics tends to follow a normal distribution around its mean. In this case, the signal-to-noise ratio-SNR is given by:

$$SNR = \frac{N}{\sqrt{N}} = \sqrt{N}$$

1.1.2 Single photon component characterisation

The characterization of single-photon components is crucial for benchmarking and evaluating these components for certain applications. A baseline characterization tool is the measurement of the single-photon detector efficiency. Decades of work on optical power metrology resulted in optical power measurement capabilities with uncertainties on the order of 0.01 % in the microwatt regime [Hou01] but range from the single photon regime [Lop15,Tho19] to hundreds of kilowatts of laser power [Wil17] albeit with higher uncertainties. Due to the history of and the tremendous capabilities in optical power metrology, we currently use a detector-based optical power traceability chain to establish a baseline characterization tool for single photon detection: a calibrated single-photon detector (SPD). Once the SPD is accurately characterized, accurate characterization of a photon source or a quantum state of light and a comparison of a quantum-enhanced protocol to be best classical protocol is possible [Lun09,Gio12,Akh11]. Eventually, this detector-based method may be replaced by a source-based method utilizing single-photon counting, and therefore also offering the unique capability of measuring optical power by counting photons [Che07].

Low-uncertainty measurements of the detection efficiency of an SPD are challenging. We define detection efficiency of an SPD as the probability of detecting a photon incident on the detector resulting in a discernible output signal. One common method of calibrating an SPD is to use of an attenuated laser source [Mar13,Lop15,Chu14]. This measurement requires accurate knowledge of the laser power at microwatt levels or lower, achieved via a calibrated optical power meter traceable to a primary standard and subsequent calibration of either variable or fixed attenuators to achieve a photon flux comparable to a stream of single photons in the femtowatt regime. A similar method makes use of an optical beamsplitter which serves to track the optical power emitted by the source [Tho19]. In this case, no attenuator calibration is required. However, the beamsplitting ratio must accurately be determined and kept stable over the course of the calibration. Besides an absolute optical power meter calibration, both methods described also require a non-linearity correction of their reference power meters [Vay00]. A direct optical power meter calibration transfer from an optical power meter to a single-photon detector was recently achieved using strong coherent laser pulses and by saturating the response of a superconducting nanowire single photon detector (SNSPD) connected to a fibre time-multiplexing loop [Tie19]. Assuming linearity of the detector response and mapping the average detector click rate as a function of loop roundtrip number allowed to extract the SPD detection efficiency. The optical power incident on the SPD was several hundreds of nanowatts. Another direct optical power transfer was achieved by calibrating an optical power meter down to the picowatt regime and transferring the optical power onto a low-efficiency, high-count rate SNSPD [Mue17]. Also, Müller *et al.* have demonstrated a method for SPD calibration with a synchrotron light source [Mul12,Mul14]. The synchrotron photon flux is linear with ring current, and thus by measurement of the ring current the synchrotron's photon flux can be tuned over many orders of magnitude without the need of attenuator calibrations. The ring current is linear with output photon flux, and therefore a non-linearity correction is not required. Another method uses a correlated photon source based on yet another spontaneous parametric down-conversion [Mig02,Pol07,Ave11,Kly80] (see Figure S1). The photon pair created allows coincident detection of

both photons to retrieve the overall path efficiencies for either of the two photons. This is inherently absolute, albeit for the efficiency of the entire source-to-detector system. Thus, when performing an experiment using correlated or entangled SPDC, the overall system loss can easily be estimated, and no independent calibration of components is necessary. Figure S1 shows the method of measuring the overall system loss using SPDC, also generally referred to the Klyshko efficiency measurement [Kly80].

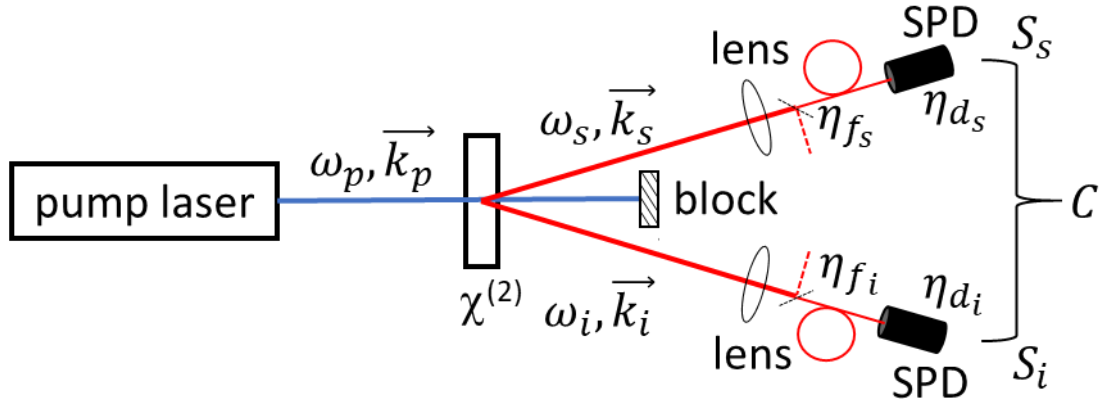


Figure S1: Klyshko efficiency measurement using spontaneous parametric down-conversion (SPDC).

Also, the international system of units (SI) has been recast based on fundamental constants and laws of nature [Wan17,Abu17]. Part of the new quantum SI could be a source- or detector-based single-photon standard. For the latter two reasons, many national metrology institutes around the world are pursuing the establishment of single-photon-based traceable or absolute calibrations of single-photon detectors and sources [Kan19,Sab19,Ade09,Jak86,Hou01,Mar85,Lop15].

Figure S1 shows a so-called Klyshko efficiency measurement using SPDC. A pump laser photon generates two daughter photons (signal and idler) obeying energy conservation, $\omega_p = \omega_s + \omega_i$ and momentum conservation, $\vec{k}_p = \vec{k}_s + \vec{k}_i$. In the non-degenerate frequency case, the signal photon refers to the higher energy photon. The pump beam is blocked by either a beam block (shown) or a spectral filter (not shown). Signal and idler photons are focused into single-mode fibre via a lens. The source-to-fibre loss is modelled by an imaginary beam splitter with transmissivity η_{f_s} and η_{f_i} for signal and idler, respectively. The single-photon detector (SPD) efficiency is given by η_{d_s} and η_{d_i} for the signal and idler SPD, respectively. Singles detection rates (S_s and S_i) and coincidence (C) detection rate can be written as: $S_s = R_0 \cdot \eta_{f_s} \cdot \eta_{d_s}$; $S_i = R_0 \cdot \eta_{f_i} \cdot \eta_{d_i}$; $C = R_0 \cdot \eta_{f_s} \cdot \eta_{d_s} \cdot \eta_{f_i} \cdot \eta_{d_i}$, where R_0 is the intrinsic SPDC generation rate at the source. The ratios C/S_i and C/S_s yield: $\eta_{f_s} \cdot \eta_{d_s} = \eta_s$ and $\eta_{f_i} \cdot \eta_{d_i} = \eta_i$, hence the overall efficiencies of the signal and idler arms, respectively. This method is used in many quantum optics experiments to quantify the overall system loss/efficiency. It also is, to first order, insensitive to the laser power, as the single pair rate (R_0) scales approximately linearly with laser power in the low pair-generation regime. In this regime higher-order pair generation is usually negligible and the errors caused by these events are small.

1.2 Exploring the foundations of quantum mechanics – non-classical nature of single photons

The notion of a wave packet for describing a photon was mentioned previously and we refer the reader to the Supplementary Information of the part 1 of the review for a more general description of a single photon in terms of wave packets rather than ‘simply’ a number N describing N photons.

What we can learn is that the wave function of a N -photon Fock state factorizes into the product of identical single-photon wave functions where each individual (single photon) wave function obeys the Maxwell's equations. This explains, for instance, why the statistical distribution of spots (flashes) recorded by Taylor in 1909 [Tay09] with a dimmed light source statistically in a two-slit experiment *à la* Young reproduces the continuous distribution derived from Maxwell's theory. This also explains why, in many situations (where thermal and laser light sources are used for instance), Maxwell's theory suffices to account for the observations. However, whenever we consider at least two single photons, entanglement is likely to be present, and a classical description *à la* Maxwell in the physical 3D space must be replaced by a description in the configuration space. This is exemplified, for instance, by the Hong-Ou-Mandel experiment which cannot be explained in terms of Maxwell fields [Gra86]. However, already in the single photon case, non-classical features such as complementarity and contextuality are present, which mark a departure with the classical description from Maxwell's equations.

1.2.1 Complementarity

Complementarity is the notion that a single measurement context usually does not exhaust information about the behavior of a quantum system [Boh49]. The best-known case is that of wave-particle duality in which interference fringes are the hallmark of the wave character, whereas information about the path a particle took through an interference setup asserts the particle character. Beyond the simple extreme cases of either perfect interference or perfect path information, an inequality [Gre88,Jae95,Eng96] bounds the sum of the squares of wave and particle characters as measured by the interference visibility and the trace distance of the different path information states, respectively. This inequality was verified for photons by Schwindt *et al.* [Sch99] using a Mach-Zehnder interferometer and also by B. Dopfer *et al.* [Dop98,Zei99] for the double slit case.

1.2.2 Quantum eraser

The quantum eraser belongs to a family of puzzling experiments where the single particle trajectory is entangled with either another quantum system as in the original proposal [Scu91], or with another of the particle's internal or external degrees of freedom. Measurements of this second observable and the choice of basis in which to measure it, will then determine whether an interference pattern is visible or not, whether the path information has been erased or not. There are various opinions on exactly what constitutes a quantum eraser experiment, which are discussed in [Kwi92]. Consequently, a series of single photon experiments [Dop98,Scu91,Kwi92,Zaj91,Her95,Pit96] demonstrated quantum erasure in different ways either via the polarization or via a correlated partner photon as a path marker.

1.2.3 Delayed choice

The idea of a quantum eraser is interwoven with the idea of a delayed choice experiments [Whe78], where the wave or particle character of the photon is decided only after the passage through (part of) the apparatus, which suggests a paradoxical back-action of the future on the past. This has been pushed to the point where the "decision" is delayed until after detection. The situation only appears paradoxical if one considers a dualist — either wave or particle — picture of the evolution. The quantum mechanical wavefunction evolves entirely unitarily up until detection. In delayed choice experiments [Dop98,Kim00,Jac07] the data is simply pre- or post-selected by the detection process according to whether path information could be obtained or not *e.g.* in [Dop98] and [Kim00], a beamsplitter either sends the photon to path detection or not. In [Jac07], a quantum random number generator makes the choice. Finally in two more recent experiments [Per12,Kai12] using explicit entanglement with another photon leaves the "choice" to the partner photon in a nonlocal way, which

can now even “choose” to reveal only partial path information. From a global viewpoint it is only the correlation with the “choice” result that filters the data to reveal an interference pattern or not.

1.2.4 Interaction-free measurement

In the same vein, the probability of firing of a detector put at the output of an interferometer (such as a Mach-Zehnder) is not the same according to our choice to block (or not) one of its arms. This makes it possible to detect the presence of an obstacle along one arm, for instance a bomb, without sending a photon at it [Eli93]. Combined with the quantum Zeno effect this idea led to the possibility of detecting the presence of an obstacle with probability close to one, accompanied by a probability for the obstacle to absorb a single photon close to zero [Kwi95a,Kwi95b,Kwi99]. Extended to scanning an object, the use of multimode interferometers, or correlated imaging, this idea leads to the field of quantum imaging, which is beyond the scope of this Review but nevertheless very interesting (see [Mor19] for instance).

1.2.5 Hardy’s paradox and contextuality

Quantum contextuality is a feature of quantum mechanics whereby measurements of quantum observables cannot simply be thought of as revealing pre-existing values. Any attempt to do so leads to values that are dependent upon which other measurements are being performed (the measurement context). More formally, the measurement result of a quantum observable is dependent upon which other commuting observables are within the same measurement set. As has been shown by Hardy [Har92], quantum correlations between entangled systems violate bounds constraining non-contextual models with nonzero probability. This property has been checked with path-polarisation entangled single photons [Kar14]. It has also been confirmed by experiments with pairs of identical single photons [Kar14,Irv05,Lun09].

1.2.6 de Broglie-Bohm interpretation and single particle non-locality

Whenever one photon at a time is sent through a Mach-Zehnder interferometer for instance (this experiment was realized by Grangier *et al.* several years ago [Gra86]) everything happens as if the photon was simultaneously present in both arms of the interferometer (bi-located) unless which-path information suffices to know through which arm the photon travels. Even in a hidden variable approach *à la* de Broglie-Bohm [Hol93], the pointlike particle supposedly passes through one slit (through one arm of the interferometer) only, but its trajectory undergoes the influence of the pilot wave which passed through the other slit (arm), so that even in this particular interpretation, some form of multilocality appears, even when only one particle is present. In the case of single photons, a more subtle form of non-locality is present [Fla16]: photon trajectories are not invariant under Lorentz transformations.

It is worth noting that in the case of fermions, it is possible to define Lorentz covariant single electron trajectories, because when the wave function of the electron obeys Dirac equation the 4-component object built with the conserved density and the current vector transforms as a Lorentz 4-vector [Hol93,Boh87]. As shown by Hardy [Har92], when more than one particle is present, a Lorentz covariant description of the trajectories is impossible and one has to invoke the existence of a privileged frame.

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