~~Siegert relation test for~~ Distinguishing thermal and pseudothermal light ~~against spontaneous emission~~by testing the Siegert relation

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Thermal light, including blackbody radiation and spontaneous emission, exhibits photon bunching, where photons arrive more closely in time than predicted by Poissonian statistics. Such sources, however, typically yield low spectral densities, limiting their practical utility. Pseudothermal light is often employed instead, owing to its higher brightness and longer coherence times that are readily accessible with standard detectors. While pseudothermal sources also exhibit photon bunching, this property on its own may not suffice to fully replicate the behavior of genuine thermal light. Here we demonstrate a method to directly test the Siegert relation for a pseudothermal light source against a spontaneous emission source, thereby probing a fundamental criterion expected of thermal light.

I. THERMAL AND PSEUDOTHERMAL LIGHT~~SPONTANEOUS EMISSION ARISES~~

Spontaneous emission arising from an ensemble of particles like atoms with motion in thermal equilibrium ~~that emit~~ is light with random phases between individual emission processes [1–4]. ~~An exampleis blackbody radiation , which produces stationary~~ Similarly, blackbody radiation forms stationary light fields across a broad frequency spectrum without fixed phase relationships between light at different locations or times [5].

Thermal light, including spontaneous emission from gas discharge lamps [6–9] and blackbody radiation [10, 11], exhibits photon bunching [12–16], ~~whereby the photons propagate~~ where the photodetection events appear closer together than as described by random Poissonian timing statistics [17]~~, i.e.~~ ; mathematically, this is expressed by a second order correlation $g^{(2)}(0) > 1$.

However, the spectral density of blackbody radiation is determined by its surface temperature, which limits its photon bunching output brightness below practical thresholds. The broadband nature of the blackbody spectrum shortens the coherence timescale of the bunching ~~behaviour~~ behavior to the femtoseconds regime, rendering its photon bunching inaccessible to standard photodetectors.

~~Therefore, alternative~~ Alternative "pseudothermal" light sources are therefore commonly employed to ~~realize~~ demonstrate photon bunching. Typical implementations include laser beams scattered from time-varying dispersive media, such as rotating ground glass ~~,~~ diffusers [18–23], or particles undergoing Brownian motion suspended in a liquid [24–27].

Such pseudothermal light sources generate bright ~~photon bunching~~ photon-bunched light owing to the underlying laser excitation, with coherence timescales long enough to be readily resolved by available photodetectors.

~~This work demonstrates~~ Here, we demonstrate that pseudothermal light can yield photon correlations distinguishable from those of thermal radiation, even though both exhibit the temporal photon bunching characteristic~~of thermal fields.~~.

II. ~~TEST BY~~ SIGNATURE PHOTON BUNCHING

~~The photon bunching output of~~ We compare two photon-bunched light sources: a thermal light source ~~is compared against that from a pseudothermal light source, corresponding to the~~ based on spontaneous emissions from a Mercury (Hg) low pressure gas discharge~~lamp against the~~ , and a pseodothermal light source, based on laser light scattered off a rotating ground glass ~~, prepared as shown in Fig~~plate(see Figs. 1a and ~~Fig. 1brespectively~~b).

~~The~~ For thermal light, the spontaneous emission around 546.1 nm from the Hg lamp is selected by a 546 nm spectral filter with a 3 nm optical passband. Multiple spectral emission lines ~~are expected~~ due to hyperfine splitting resulting from a natural mix ~~ratio~~ of Hg isotopes with non-zero nuclear spins are captured. The presence of multiple emissions that are mutually incoherent ~~with each other should therefore reduce the measured~~ reduce the resulting $g^{(2)}(0)$ from the ideal ~~peak~~ thermal light value of 2. The spectrally filtered light is projected into a single spatial mode by a single mode optical fibre, and transmitted through a linear polariser to increase interferometric visibility.

~~For the pseudothermal light source,~~ Pseudothermal light is prepared by scattering light from a 780 nm distributed feedback laser ~~is~~ focused on a ~~reflective~~ ground glass difffuser of grit 1500 ~~as shown in~~ (see Fig. 1b). The bare tip of ~~a single mode fibre~~ an optical fiber (single mode for 780 nm) is positioned about 19 cm away from

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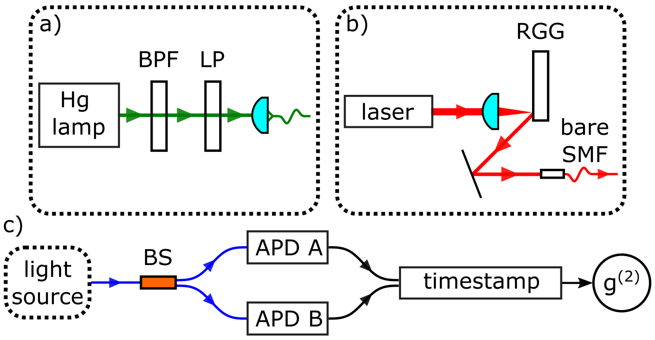

FIG. 1. Experimental setups for the a) thermal Thermal light source via based on a Mercury (Hg) vapor gas discharge lamp, b) pseudothermal light source from generated by laser light scattered off a rotating ground glass diffuser, and . c) Hanbury-Brown–Twiss interferometer to measure the second-order photon timing photodetection time correlations $g^{(2)}(\tau)$. (BPF: bandpass filter, LP: linear polariser, RGG: rotating ground glass, BS: fibre-based beamsplitter, APD: avalanche photodetectors, SMF: single mode fibre)

the illuminated spot to collect reflected scattered light scattered from the ground glass.

The laser light Light scattered from a rotating ground glass is expected to produce photon bunching that can be described by the show photon bunching with a second order correlation function $g^{(2)}(\tau)$ with a Gaussian profile [28–31], such that $g^{(2)}(\tau) = 1 + \exp\left[-\left(\frac{\tau}{\tau_{\mathrm{RGG}}}\right)^2\right]$,

$$g^{(2)}(\tau) = 1 + e^{-\left(\frac{\tau}{\tau_{\mathrm{RGG}}}\right)^2}, \quad (1)$$

where τ_{RGG} is the coherence timescale of the photon bunching by a rotating ground glasssignature of this souce.

The focal spot size ϕ of the beam on the ground glass surface is about $4\,\mu$m in diameter, and positioned at a radial distance R of about 10 mm from the rotation axis. With the scattered light collected at a distance of 19 cm away, which is significantly larger than the spot size of $\phi = 4\,\mu$m, the value of coherence timescale τ_{RGG} can thus be is predicted [28–31] using as $\tau_{\mathrm{RGG}} \approx \frac{\phi T}{4\pi R}$. The motor rotates the ground glass with a period T of about 4$T \approx 4$ ms, corresponding to an expected coherence timescale τ_{RGG} of around 130resulting in $\tau_{\mathrm{RGG}} \approx 130$ nsfor the resultant photon bunching.

A To detect for photon bunching signatures in light from the two sources, a Hanbury-Brown–Twiss (HBT) interferometer as shown in (see Fig. 1cis used to measure the second-order photon correlation $g^{(2)}(\tau)$ of the light output from the two light sources to detect for photon bunching signatures. Light from the test) is used. For this, light from a source is sent through a beamsplitter to illuminate a pair of actively quenched Silicon avalanche photodiodes (APD). The photo-detection events were then timestampedby a field programmable gate array device. The timestamp series were then histogrammedinto two-photoevent coincidences and , from which detection time differences between the detectors were histogrammed, and histograms were fitted with Gaussian models as illustrated in Fig. 2.

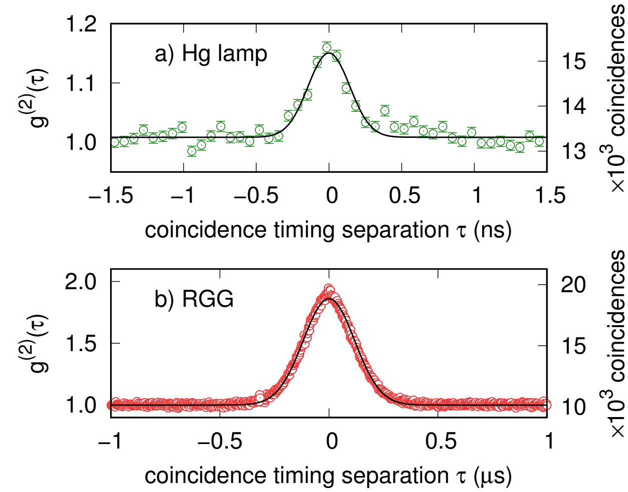

FIG. 2. Photon bunching signatures. (a) The Hg lamp exhibits photon bunching with a peak $g^{(2)}_{Hg}(0) = 1.142 \pm 0.007$ and a coherence timescale time scale $\tau_{Hg} = 0.35 \pm 0.02$ ns (both numeric values are results of fits, solid line). Scattered (b) Results for scattered light from the rotating ground glassproduces a bunching peak , $g^{(2)}_{RGG}(0) = 1.859 \pm 0.002$with a timescale of , $\tau_{RGG} = 277.5 \pm 0.6$ ns.

The light Light from both the Hg lamp and the rotating ground glass exhibit photon bunching. However, the $g^{(2)}_{Hg}(0) = 1.142$ The $g^{(2)}_{Hg}(0) = 1.142 \pm 0.007$ is significantly lower than the ideal thermal peak of theoretical thermal light peak $g^{(2)}(0) = 2$, and the as anticipated from the contribution of different spectral lines. Furthermore, the short coherence timescale of $\tau_{Hg} = 0.35$ $\tau_{Hg} = 0.35 \pm 0.02$ ns makes it difficult for standard photodetectors to timing-resolveresolve the timing of photodetection pairs.

Whereas In contrast, the output from the rotating ground glass exhibits a noticeably stronger bunching behaviour at a peak $g^{(2)}_{RGG}(0) = 1.859$, with with $g^{(2)}_{RGG}(0) = 1.859 \pm 0.002$, and a coherence timescale $\tau_{RGG} = 277.5 \pm 0.6$ ns that is 3 orders longerat $\tau_{RGG} = 277.5$ ns , and thus straightforward to resolve with readily available detectors. This makes the scattered scattering light from a rotating ground glass a common choice as a popular pseudothermal light source to replace spontaneous emission in thermal light experiments that exploit the photon bunchingpropertydemonstrate photon bunching.

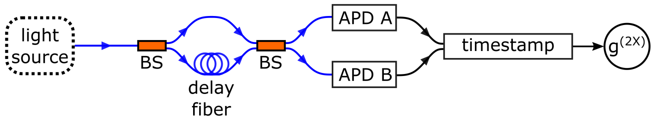

FIG. 3. Experimental setup for measuring interferometric photon correlations $g^{(2X)}(\tau)$. The delay fibers are chosen to introduce an optical delay of $\Delta = 2.22\,\mu$s for testing scattered light from the rotating ground glass, and $\Delta = 10\,$ns for ~~when~~ testing light from the Hg lamp~~, or about 1 order longer than their respective coherence times to separate the bunching peaks~~. (BS: Beamsplitter, APD: avalanche photodetectors)

III. ~~TEST BY~~ TESTING THE SIEGERT RELATION

Thermal light exhibits photon timing correlations, including the characteristic photon bunching, that satisfy the Siegert relation [32–37] ~~as described by~~

$$g^{(2)}(\tau) = 1 + |g^{(1)}(\tau)|^2\,, \qquad (2)$$

where $g^{(1)}(\tau)$ is the first order correlation function, and its modulus $|g^{(1)}(\tau)|$ is the interferometric visibility.

The $g^{(2)}(\tau)$ can be determined by photon bunching measurements in a HBT interferometer as shown in the previous section, and is ~~so adopted as the~~ adopted as a general test for thermal light due to its practical ease and convenience.

The $g^{(1)}(\tau)$ can be ~~deteremined by~~ obtained with a Michelson interfereometer ~~scanned~~ scanning over a range of optical path length differences. This can be difficult as the scanning range needs to be on the order of the coherence timescale~~, i. e. to~~. For the example above with $\tau_{RGG} = 277.5\,$ns, this would necessitate an impractical scan over 83 metres ~~for $\tau_{RGG} = 277.5\,$ns. This is further complicated by the phase sensitivity of $g^{(1)}(\tau)$, whereas $g^{(2)}(\tau)$ is phase independent, which requires sub-wavelength optomechanical stability of the Michelson interferometer, i.e. optical paths to be stable in the order of hundreds of nanometres. Sub-micrometre stability over a hundred metres scanning range translates to an overall ratio of 10^{-9} which is technically challenging.~~ path length difference.

~~An~~ Alternatively, an asymmetric Mach-Zehnder interferometer ~~as shown in Fig. 3 is~~ can be used to test ~~for~~ the Siegert relation ~~, by measuring~~ via an interferometric correlation $g^{(2X)}(\tau)$ (see Fig. 3). This reveals both the second order correlation function $g^{(2)}(\tau)$ and the modulus of the first order correlation function $|g^{(1)}(\tau)|$ simultaneously. This method has the advantage of being phase independent by measuring $|g^{(1)}(\tau)|$ instead of $g^{(1)}(\tau)$, and does not require ~~repeating measurements over~~ a range of optical path length differences.

~~The Hg lamp outputs 2 bunching side peaks $g^{(2X)}_{Hg}(\pm\Delta) = 1.044 \pm 0.003$ at reduced amplitudes, with $\tau_{Hg} = 0.41 \pm 0.03\,$ns. Scattered light from the rotating ground glass outputs a central bunching peak (blue dashed lines) $g^{(2X)}_{RGG}(0) = 1.412 \pm 0.002$ and 2 smaller side peaks $g^{(2X)}_{RGG}(\pm\Delta) = 1.206 \pm 0.001$, with $\tau_{RGG} = 172.8 \pm 0.6\,$ns. However, although the amplitude of $|g^{(1)}(0)|^2 = 0.421 \pm 0.003$ is similar to the central bunching peak amplitude, but its coherence timescale $\tau_c = 149 \pm 2\,$ns is shorter than τ_{RGG}, and so do not fully cancel out the bunching feature around $\tau = 0$.~~

The respective light fields $E_{A,B}(t)$ at the output ports A, B of ~~the~~ an intensity-balanced interferometer are

$$E_{A,B}(t) = \frac{E(t) \pm E(t+\Delta)}{\sqrt{2}}\,, \qquad (3)$$

where $E(t)$ is the input light field ~~into the interferometer from the test source, with the $\pm$ sign difference is a result of a relative π phase acquired by one of the fields at the beamsplitter [38]. The~~ of the interferometer. The fixed optical delay Δ is introduced by a ~~delay~~ single-mode optical fiber~~for 780 nm~~, chosen to be much larger than the expected characteristic coherence time of the light.

Photoevents in our implementation are detected by Silicon avalanche photodetectors (APDs) at the output ports of the interferometer and timestamped. The interferometric photon correlation $g^{(2X)}(\tau)$ between the photodetectors ~~are~~ is

$$g^{(2X)}(\tau) = \frac{\langle E^*_A(t+\tau)E^*_B(t)E_B(t)E_A(t+\tau)\rangle}{\langle E^*_A(t)E_A(t)\rangle\langle E^*_B(t)E_B(t)\rangle} \qquad (4)$$

where $\langle\ldots\rangle$ is the ensemble average over measurement time t, and τ is the two-photoevent coincidence timing separation.

Upon expansion of Eqn. ~~4~~ (4) using Eqn. ~~3~~(3), it can be shown [39, 40] that the non-zero terms are

$$\begin{aligned} g^{(2X)}(\tau) =& \frac{1}{4}\,g^{(2)}(\tau+\Delta) + \frac{1}{4}\,g^{(2)}(\tau-\Delta) \\ &+ \frac{1}{2}[g^{(2)}(\tau) - |g^{(1)}(\tau)|^2]\,. \end{aligned} \qquad (5)$$

The photon bunching $g^{(2)}(\tau)$ ~~peak of a test light source~~ signature would now manifest into ~~2~~ two side peaks $g^{(2X)}(\tau)$ at 1/4 of its original amplitude, positioned at ~~$\pm\Delta$ timing delays~~ photoddetection time delays $\tau = \pm\Delta$.

If the test light ~~source obeys Siegert relation, such that $g^{(2)}(\tau) - |g^{(1)}(\tau)|^2 = 1$,~~ obeys the Siegert relation Eq. (2), and recalling that the optical delay length is chosen such that $g^{(2)}(\Delta) = 1$, then $g^{(2X)}(0) = \frac{1}{4} + \frac{1}{4} + \frac{1}{2} = 1$. This results in a flat coincidence floor around $\tau = 0$~~, which corresponds to the~~.

Experimental results of $g^{(2X)}(\tau)$ ~~measurements~~ for the two light sources tested in this work are shown in Fig. 4~~, suggesting that Hg lamp emits thermal light obeying~~. The flat region near $\tau = 0$ for light emitted by the Hg lamp suggests to obey the Siegert relation, compatible with expectations for thermal light.

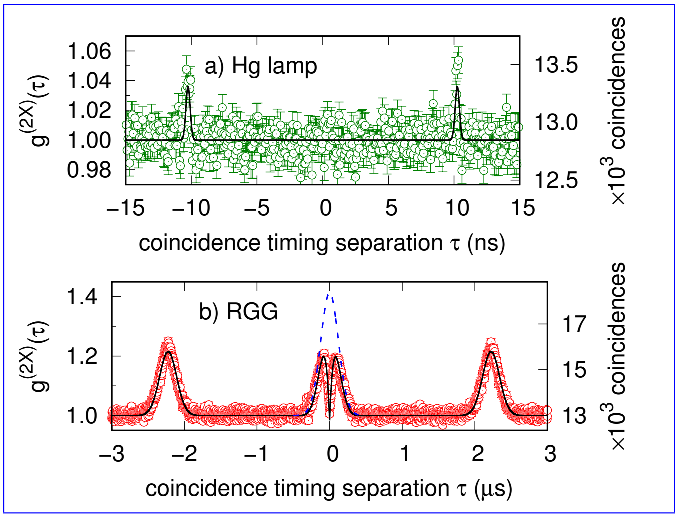

FIG. 4. Experimental results for interferometric photon correlations. (a) Light from the Hg lamp shows two bunching side peaks $g^{(2X)}_{Hg}(\pm\Delta) = 1.044 \pm 0.003$ at reduced amplitudes, with $\tau_{Hg} = 0.41 \pm 0.03\,\text{ns}$. (b) Scattered light from the rotating ground glass exhibits outputs a central bunching peak (blue dashed lines) $g^{(2X)}_{RGG}(0) = 1.412 \pm 0.002$ and two smaller side peaks $g^{(2X)}_{RGG}(\pm\Delta) = 1.206 \pm 0.001$, with $\tau_{RGG} = 172.8 \pm 0.6\,\text{ns}$. The solid line shows a fit to Eq. (5).

If the test light source violates Siegert relation, such that $g^{(2)}(\tau) - |g^{(1)}(\tau)|^2 \neq 1$, then Light prepared by the rotating ground glass setup shows a non-flat bunching feature is expected around featurearound $\tau = 0$, which corresponds to the $g^{(2X)}(\tau)$ measurements shown in clearly violating the Siegert relation ($g^{(2)}(\tau) - |g^{(1)}(\tau)|^2 \neq 1$, see Fig. 4 , suggesting that scattered light from a b)). The fit of the experimental $g^{(2X)}_{RGG}(\tau)$) to Eq. (5) yields $g^{(2X)}_{RGG}(0) = 1.412 \pm 0.002$ and $-|g^{(1)}(0)|^2 = -0.421 \pm 0.003$. However, although the amplitude of $|g^{(1)}(0)|^2$ is similar to the central bunching peak amplitude, its coherence timescale $\tau_c = 149 \pm 2\,\text{ns}$ is shorter than τ_{RGG}, and so it does not fully cancel out the bunching feature around $\tau = 0$.

This deviation from the expectation for thermal light suggests the rotating ground glass violates the Siegert relation and is thus not thermal lightsource to be considered a pseudothermal light source, and not a thermal light source.

IV. CONCLUSION

We observe a violation find that the test of the Siegert relation for light scattered off a rotating ground glass diffuser, suggesting that pseudothermal light can be distinguishable from thermal light, by measuring for photon correlations other than photon bunching. The light emission from a Mercury vapor lamp obeys the Siegert relation, supporting spontaneous emission as thermal lightas expected. can be a useful tool to distinguish thermal from pseudothermal light, providing additional information beyond the observation of photon bunching. Therefore, probing for the interferometric photon correlation $g^{(2X)}(\tau)$ can be a stronger witness of thermal light.

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