Quantum detector tomography of MgB_2 nanowire

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Abstract: We perform quantum detector tomography of a novel, unknown detector – superconducting magnesium diboride nanowire, and show that reconstructed POVM elements provide insights into underlying detection mechanism and multiphoton detection efficiencies.

Quantum tomography is a comprehensive tool that fully characterizes all three stages of a quantum experiment: state preparation, evolution (process), and measurement (detector). Among this triad, quantum state and process tomography took off quickly and became widely applied methods. Meanwhile, quantum detector tomography (QDT) is rarely used as it is overshadowed by traditional calibration methods, based on determining, e.g., detector efficiency and noise-equivalent power. Yet, these traditional methods cannot provide a complete and accurate description of quantum measurements, and QDT is unavoidable for real-world quantum information applications.

QDT characterizes detectors by identifying their Positive Operator-Valued Measure (POVM) elements, which bridge the quantum system with classical detector outputs. This characterization involves reconstructing the detector's POVM elements, $\boldsymbol{\pi_m}$, through the analysis of a statistical distributions of detector responses to a set of *known* input states, $\{\boldsymbol{\rho}\}$. To date, QDT has been developed and successfully experimentally realized for semiconducting detectors, click/no click avalanche photodiodes (APDs) and photon-number-resolving detectors (time-multiplexed APDs) [1]. However, only a few attempts [2] have been made to adapt QDT for superconducting nanowire single-photon detectors (SNSPDs), which are increasingly preferred in quantum experiments for their superior performance compared to APDs. The main barrier to this adaptation has been the complexity of SNSPD's detection mechanism. Previously, QDT was implemented on a *constriction-like* superconducting detector with a tiny sensitive area roughly equivalent to the non-superconducting region induced by photon absorption (~100 nm by 100 nm). Yet, this approach remains unapplicable to practical devices with large sensitive areas like SNSPDs.

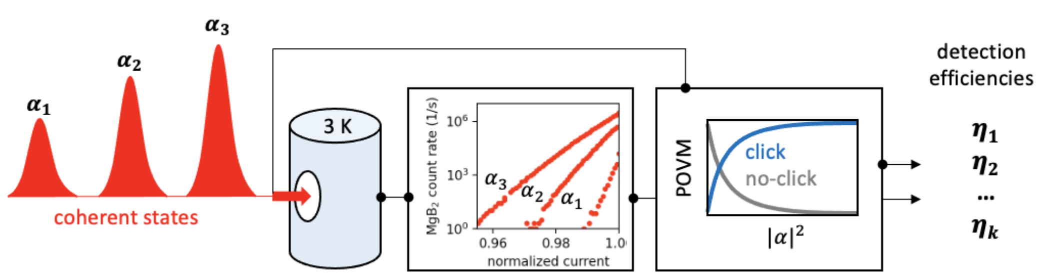

Fig. 1. **Schematic of quantum detector tomography of an MgB_2 superconducting nanowire.** Coherent light from a femtosecond laser is sent in free space to MgB_2 nanowire mounted inside an optical cryostat at 3 K. By varying the coherent light intensities $|\alpha|^2$ and measuring the count rate of the MgB_2 detector, we reconstruct POVM elements and multiphoton detection efficiencies, η_k.

Here, we develop QDT of superconducting large-area detectors and apply it for the characterization of a superconducting nanowire made of magnesium diboride (MgB_2), as sketched in Fig.1. The localized nature of photon detection by a superconducting nanowire dictates that the detection efficiency, before reaching saturation, is significantly influenced by the number of absorbed photons. This means that despite functioning essentially as binary (click/no-click) detectors without photon-number-resolution capability, the click probability correlates with the number of photons absorbed locally in the same site. The detector's POVM elements can be then identified in the photon number (Fock) basis with the POVM for "no-click" and "at least one click" written as

$$\boldsymbol{\pi_{no-click}} = \sum_{n=0}^{\infty}(\mathbf{1}-\boldsymbol{\eta_k})\, \boldsymbol{p_{j,k}}\, |\boldsymbol{n}\rangle\langle\boldsymbol{n}|,$$

$$\boldsymbol{\pi_{click}} = \mathbf{1} - \boldsymbol{\pi_{no-click}},$$

where, by accounting for photon distribution over the detector's sensitive area (partition problem), denoted by the probability $p_{j,k}$, we find detection efficiency of multiphoton events, η_k.

We apply the modified QDT method to characterize a *novel* detector made of MgB_2 superconductor, which has been proposed as a very promising high-Tc platform for SNSPDs [3]. The detector consisted of a straight nanowire (8 nm thick, 150 nm wide, 100 µm long) and exhibited a high critical current of ~539 μA at 3 K and a critical temperature of ~34 K. Given the practical challenge in generating Fock states, we adopt the most convenient approach instead and use coherent states from a conventional laser for our experiments. MgB_2 nanowire was exposed to coherent pulsed source with a wavelength of 800 nm and a pulse duration of 30 fs to assure simultaneous photon absorption. Fig.2 shows the measured data fitted with our modified QDT method. These fits incorporate detection efficiencies to multiphoton evens, which exhibit non-linear dependence on the photon number, trending towards unity with increasing photon numbers.

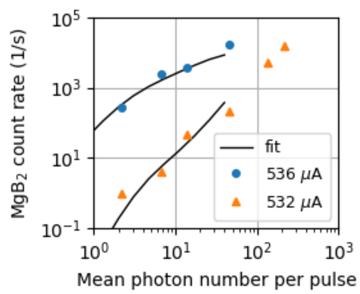

Fig. 2. **Measured MgB_2 count rate vs. mean photon number per femtosecond laser pulse.** Data points: experimental data obtained at two bias currents indicated; curves: fits derived with our introduced QDT method.

In conclusion, following the general microscopic picture of photon detection by a superconducting large-area detector, we introduced the QDT method that accounts for the detection efficiencies of multiphoton events. We have applied this method to characterize a novel, unknown superconducting MgB_2 detector. The retrieved multiphoton detection efficiencies are physically reasonable and provide valuable information on the detection mechanisms. We argue that this method accurately describes quantum measurement and has a wide area of applicability.

References

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