Robust Weak Measurements with Certified Single Photons

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Since their introduction, weak measurements (WMs) and weak values (WVs) have served as a cornerstone for investigating quantum measurement theory, as well as a powerful tool in quantum metrology and sensing. Their exotic features - such as the possibility of yielding anomalous values (i.e., imaginary or unbounded by the observable eigenvalue spectrum) - have been demonstrated and exploited in numerous applications in quantum metrology and quantum information.

Nevertheless, the interpretation of WVs and the quantumness of their nature remain controversial. One of the main objections against their quantumness, for example, stems from the fact that they require a weak coupling followed by a post-selection. Due to the coupling weakness, observing a WV requires averaging over an ensemble. While averaging is a standard practice, however, its combination with post-selection is not: consequently, the legitimacy of WV statistical estimation has been put into question.

To reach a conclusive point in this debate, we devised and experimentally demonstrated a novel weak-interaction-based measurement protocol termed Robust Weak Measurement (RWM) [1,2]. In this protocol, rather of averaging over multiple acquisitions, even a single readout of the measuring device provides a reliable estimate of an (anomalous) WV.

In our proof-of-principle experimental implementation of RWM, we extracted the WV of the polarization of a single photon sent through a series of N=7 identical stages, each consisting of pre-selection, weak coupling and post-selection. Pre- and post-selection tune the system to detect an arbitrary (anomalous) WV.

Our first results [1] demonstrated the possibility of reliably extracting an (anomalous) WV with a single click of the detector. However, due to technical limitations, these results were obtained with a multi-thermal light source attenuated at the single photon level and detected, by an EM-CCD camera. To overcome these limitations and conclusively establish the single-particle nature of the effect, our newest results [2], obtained using a heralded single-photon source and a spatially resolved SPAD array, confirm the RWM capability to extract an (anomalous) WV even from a single-photon, thereby certifying the genuinely single-particle, nonclassical nature of WVs. Furthermore, this experiment suggests a viable possibility for iterative amplification methods, paving the way for future practical applications in quantum metrology and other quantum-technology-related fields.

References

[1] E. Rebufello et al., Light: Sci. & Appl. 10, 106 (2021).

[2] E. Rebufello et al., Adv Quantum Technol. 8, 2400482 (2025)