Quantum measurements in weak coupling regime: From Sequential weak values to protective measurements

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Abstract: Quantum measurements in weak coupling regime represent a new interesting paradigm with significant applications both conceptual and practical. Here we present several experimental achievements exploiting weak values, and the first realization of protective measurements.
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1. Introduction

The measurement problem in quantum mechanics is nowadays a research topic of the utmost relevance for many aspects, e.g. the fact that quantum observables can have undetermined values “collapsing” on a specific one only when a strong measurement (i.e. a projection) is performed. This implies that measuring one observable completely erases the information on its conjugated one, forbidding simultaneous measurement of non-commuting observables on the same quantum state.

Recently, new quantum measurement paradigms emerged, allowing to avoid the wave function collapse by means of a weak coupling between the state and the pointer.

A first example is represented by weak values [1,2], firstly realized in [3-5], that correspond to the matrix element of an observable evaluated between a pre- and a post-selected state.

Aside allowing to address foundational questions [6-11] like Contextuality, weak values can also be seen as a quantum metrology tool able to achieve high-precision measurements, as tiny spin Hall effect [12] or small beam deflections [13-16], and quantum states characterization [17].

Furthermore, since weak measurements do not make the wave function collapse, they may allow gathering simultaneous information of non-commuting observables [18], impossible with traditional “strong” measurements.

2. Weak values and Contextuality

After an initial introduction to weak measurements and a discussion of the regime of their application [19], in this talk we present an experiment addressed to explore the connection between anomalous weak values and Contextuality [20] following the theoretical proposal of Ref. [21]. A clear violation of the inequality proposed in [21] is obtained while satisfying all the theoretical requests, unequivocally demonstrating the contextual nature of weak measurements.

3. Sequential Weak Values with single photons and applications

Then, we show the results related to the first experimental realization of sequential weak measurements [22], i.e. a joint measurement of the weak value of (incompatible) polarizations of a single photon, discussing possible future applications.

As a first application of this scheme, we describe our work concerning a test of Leggett-Garg inequalities based on sequential weak values [23], a result that can be used as a measure of “quantumness”.

4. Protective measurements

A second example of measurement in weak coupling regime is represented by protective measurements [24], a new paradigm granting the possibility of measuring the expectation value of a quantum observable with a single measurement on a single particle. They are realized coupling the state to a pointer in weak coupling regime and providing a “protection” of the state (e.g. through quantum Zeno effect or adiabatic evolution) based on some a priori information on state itself.

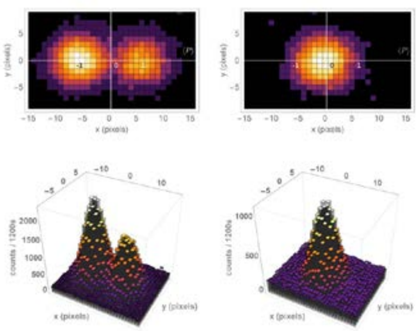

Fig.1 Comparison of a projective and a protective measurement for single photons: in the first case the average polarization derives from the average of the two peaks corresponding to projecting onto horizontal (H) or vertical (V) polarization, while protective measurements directly provide the polarization average value.

This idea prompted a wide debate on the interpretation of the wave function (e.g on its ontic nature), but we have also demonstrated a significant advantage of this measurement protocol in certain experimental configurations.

This talk will end presenting the first experimental realization of protective measurements [25], where this advantage is properly discussed, showing a certain analogy with genetic algorithm leading to the realization of genetic quantum measurements [26].

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