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Can a future choice affect a past measurement's outcome?

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ABSTRACT

An EPR experiment is studied where each particle within the entangled pair undergoes a few weak measurements (WMs) along some pre-set spin orientations, with the outcomes individually recorded. Then the particle undergoes one strong measurement along an orientation chosen at the last moment. Bell-inequality violation is expected between the two final measurements within each EPR pair. At the same time, statistical agreement is expected between these strong measurements and the earlier weak ones performed on that pair. A contradiction seemingly ensues: (i) Bell's theorem forbids spin values to exist prior to the choice of the orientation measured; (ii) A weak measurement is not supposed to determine the outcome of a successive strong one; and indeed (iii) Almost no disentanglement is inflicted by the WMs; and yet (iv) The outcomes of weak measurements statistically agree with those of the strong ones, suggesting the existence of pre-determined values, in contradiction with (i). Although the conflict can be solved by mere mitigation of the above restrictions, the most reasonable resolution seems to be that of the Two-State-Vector Formalism (TSVF), namely, that the choice of the experimenter has been encrypted within the weak measurement's outcomes, even before the experimenters themselves know what their choice will be.

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0. Introduction

Bell's theorem [1] has dealt the final blow on all hopes to explain the EPR correlations [2] as previously determined. Bell proved that these cosine-like correlations also depend on the two particular spin-orientations chosen for each measurement. As these choices can be made *at the last moment*, the resulting combinations of measurement outcomes, being mutually exclusive, *could not co-exist in advance*. Consequently, nonlocal effects between the particles have been commonly accepted as the only remaining explanation.

A variation of the EPR experiment is hereby presented, however, that suggests a simpler local explanation, namely allowing causation to be time-symmetric in the quantum realm. Then, what appears to be nonlocal in *space* turns out to be perfectly local in *spacetime*. This account's gist is given in Fig. 2.

The outline of this paper is as follows. Section 1 introduces the foundations of the Two-State-Vector Formalism (TSVF) and 2 weak measurement (WMs). 3 describes a combination of strong and weak measurements on a single particle illustrating a prediction of TSVF. In 4 we proceed to the EPR–Bell version of this experiment. Sections 5–6 discuss and summarize the predicted outcomes' bearings.

1. A particle's state between two noncommuting measurements

Consider a particle undergoing two consecutive strong (*i.e.*, projective) measurements, along the co-planar spin orientations α and β (the strong–weak distinction will be further discussed in Section 2). The correlation between their outcomes depends on their relative angle $\theta_{\alpha\beta}$:

$$\langle \sigma_\alpha \sigma_\beta \rangle = \cos\theta_{\alpha\beta}. \tag{1}$$

Also, by the uncertainty relations between spin operators, these two measurements disturb each other's outcomes: If, *e.g.*, the α measurement is repeated after the β, when the two directions are orthogonal, then the initial value of the *spin-*α measurement may flip to the opposite value with probability of 1/2.

Aharonov, Bergman and Lebowitz (ABL) [3] argued that, at any time between the two measurements, the state of the particle is equally determined by *both* backward and forward time-evolving boundary conditions. The probability for measuring the eigenvalue c_j of the observable c, given the initial and final states $|\Psi(t')\rangle$ and $\langle\Phi(t'')|$, respectively, is described by the symmetric formula

$$P(c_j) = \frac{\left|\langle\Phi(t) \mid c_j\rangle\langle c_j \mid \Psi(t)\rangle\right|^2}{\sum_i |\langle\Phi(t) \mid c_i\rangle \langle c_i \mid \Psi(t)\rangle|^2}, \tag{2}$$

thus having a *definite* value which agrees with both outcomes due to two state-vectors, one evolving from the past

$$|\psi(t)\rangle = \exp\left(\int_{t'}^{t} -iH/\hbar dt\right) |\psi(t')\rangle, \quad t > t', \tag{3}$$

and the other from the future:

$$\langle\Phi(t)| = \langle\Phi(t'')| \exp\left(\int_{t''}^{t} iH/\hbar dt\right), \quad t < t'', \tag{4}$$

creating the two-state-vector

$$\langle\Phi(t'')|\ |\psi(t')\rangle, \tag{5}$$

which holds for *every* intermediate moment in the evolution of the quantum system. This combination of forward and backward-evolving wavefunctions taken from the two Hilbert spaces, is argued to better describe a quantum system between two strong measurements. It is also the one which gives rise to the so called "weak value" [4–8].