

8.20: GHZ Four-Photon Entanglement Analyzed Using Tensor Algebra

This tutorial analyzes the results reported in "Experimental Violation of Local Realism by Four-Photon GHZ Entanglement" by Zhao, et al. and published in *Physical Review Letters* on October 31, 2003.

The null vector and required photon polarization states:

$$N = \begin{pmatrix} 0 \\ 0 \end{pmatrix} \quad H = \begin{pmatrix} 1 \\ 0 \end{pmatrix} \quad V = \begin{pmatrix} 0 \\ 1 \end{pmatrix} \quad H = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ 1 \end{pmatrix} \quad V = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ -1 \end{pmatrix} \quad L = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ -i \end{pmatrix} \quad R = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ i \end{pmatrix}$$

To facilitate tensor vector multiplication the polarization states are stored in the left column of a 2x2 matrix using the null vector

$$H = \text{augment}(H, N) \quad V = \text{augment}(V, N) \quad H' = \text{augment}(H', N) \quad V' = \text{augment}(V', N) \quad R = \text{augment}(R, N) \quad L = \text{augment}(L, N)$$

$$H = \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} \quad V = \begin{pmatrix} 0 & 0 \\ 1 & 0 \end{pmatrix} \quad H' = \begin{pmatrix} 0.707 & 0 \\ 0.707 & 0 \end{pmatrix} \quad V' = \begin{pmatrix} 0.707 & 0 \\ -0.707 & 0 \end{pmatrix} \quad R = \begin{pmatrix} 0.707 & 0 \\ 0.707i & 0 \end{pmatrix} \quad L = \begin{pmatrix} 0.707 & 0 \\ -0.707i & 0 \end{pmatrix}$$

Operators:

$$H'V' = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \quad RL = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}$$

Eigenvalues of various polarization states:

$$H'V'H' = \begin{pmatrix} 0.707 & 0 \\ 0.707 & 0 \end{pmatrix} \quad H'V'V' = \begin{pmatrix} -0.707 & 0 \\ 0.707 & 0 \end{pmatrix} \quad RL R = \begin{pmatrix} 0.707 & 0 \\ 0.707i & 0 \end{pmatrix} \quad RL L = \begin{pmatrix} -0.707 & 0 \\ 0.707i & 0 \end{pmatrix}$$

The initial GHZ four-photon entangled state:

$$\Psi = \frac{1}{\sqrt{2}}(H_1V_2V_3H_4 + V_1H_2H_3V_4)$$

$$|\Psi\rangle = \frac{1}{\sqrt{2}} \left[\begin{pmatrix} 1 \\ 0 \end{pmatrix} \otimes \begin{pmatrix} 0 \\ 1 \end{pmatrix} \otimes \begin{pmatrix} 0 \\ 1 \end{pmatrix} \otimes \begin{pmatrix} 1 \\ 0 \end{pmatrix} + \begin{pmatrix} 0 \\ 1 \end{pmatrix} \otimes \begin{pmatrix} 1 \\ 0 \end{pmatrix} \otimes \begin{pmatrix} 1 \\ 0 \end{pmatrix} \otimes \begin{pmatrix} 0 \\ 1 \end{pmatrix} \right]$$

Initial state set up in tensor format.

$$\Psi_i = \frac{1}{\sqrt{2}}(\text{submatrix}(\text{kroncker}(H, \text{kroncker}(V, \text{kroncker}(V, H))))$$

$$+ \text{kroncker}(V, \text{kroncker}(H, \text{kroncker}(H, V))), 1, 16, 1, 1))$$

$$\Psi^T = (0 \ 0 \ 0 \ 0 \ 0 \ 0 \ 0.707 \ 0 \ 0 \ 0.707 \ 0 \ 0 \ 0 \ 0 \ 0 \ 0)$$

The authors initially consider three measurements which are summarized below. It is shown that the initial photon state is an eigenstate of each of the operators with eigenvalue +1. In the operators x refers to a linear polarization measurement (H'V') and y refers to a circular polarization measurement (RL). The experimental results are reported in Figure 3 of the paper. Below quantum mechanical (QM) calculations (predictions) are compared with experimental outcomes. QM agrees with experiment.

The following calculations are facilitated by the following general expression for the measurement eigenstates.

$$\Psi(a, b, c, d) = \text{submatrix}(\text{kroncker}(a, \text{kroncker}(b, \text{kroncker}(c, d))), 1, 16, 1, 1)$$

σ_{xxxx} experiment:

Operator:

$$\sigma_{xxxx} = \text{kroncker}(H'V', \text{kroncker}(H'V', \text{kroncker}(H'V', H'V')))$$

Eigenvalue/Expectation Value:

$$\Psi_i^T \sigma_{xxxx} \Psi_i = 1$$

Observed: H'H'H'H', H'H'V'V', H'V'H'V', H'V'V'H', V'H'H'V', V'H'V'H', V'V'H'H' and V'V'V'V'.

$$(|\Psi(H', H', H', H')^T \Psi_i|)^2 = 0.125 \quad (|\Psi(H', H', V', V')^T \Psi_i|)^2 = 0.125 \quad (|\Psi(H', V', V', H')^T \Psi_i|)^2 = 0.125 \quad (|\Psi(H', V', V', H')^T \Psi_i|)^2 = 0.125$$

$$(|\Psi(V', H', H', V')^T \Psi_i|)^2 = 0.125 \quad (|\Psi(V', H', V', H')^T \Psi_i|)^2 = 0.125 \quad (|\Psi(V', V', H', H')^T \Psi_i|)^2 = 0.125 \quad (|\Psi(V', V', V', V')^T \Psi_i|)^2 = 0.125$$

σ_{xyxy} experiment:

Operator:

$$\sigma_{xyxy} = \text{kroncker}(H'V', \text{kroncker}(RL, \text{kroncker}(H'V', RL)))$$

Eigenvalue/Expectation Value:

$$\Psi_i^T \sigma_{xyxy} \Psi_i = 1$$

Observed: H'RH'R, H'RV'L, H'LV'L, H'LV'R, V'RH'L, V'RV'R, V'LV'R and V'LV'L.

$$\begin{aligned} (|\Psi(H', R, H', R)^T \Psi_i\rangle)^2 &= 0.125 & (|\Psi(H', R, V', L)^T \Psi_i\rangle)^2 &= 0.125 & (|\Psi(H', L, H', L)^T \Psi_i\rangle)^2 &= 0.125 & (|\Psi(H', L, V', R)^T \Psi_i\rangle)^2 &= 0.125 \\ (|\Psi(V', R, H', L)^T \Psi_i\rangle)^2 &= 0.125 & (|\Psi(V', R, V', R)^T \Psi_i\rangle)^2 &= 0.125 & (|\Psi(V', L, H', R)^T \Psi_i\rangle)^2 &= 0.125 & (|\Psi(V', L, V', L)^T \Psi_i\rangle)^2 &= 0.125 \end{aligned}$$

σ_{xxyy} experiment:

Operator:

$$\sigma_{xxyy} = \text{kroncker}(H'V', \text{kroncker}(H'V', \text{kroncker}(RL, RL)))$$

Eigenvalue/Expectation Value:

$$\Psi_i^T \sigma_{xxyy} \Psi_i = 1$$

Observed: H'H'RR, H'H'LL, H'V'RL, H'V'LR, H'V'RL, V'H'LR, V'V'RR and V'V'LL.

$$\begin{aligned} (|\Psi(H', H', R, R)^T \Psi_i\rangle)^2 &= 0.125 & (|\Psi(H', H', L, L)^T \Psi_i\rangle)^2 &= 0.125 & (|\Psi(H', V', R, L)^T \Psi_i\rangle)^2 &= 0.125 & (|\Psi(H', V', L, R)^T \Psi_i\rangle)^2 &= 0.125 \\ (|\Psi(V', H', R, L)^T \Psi_i\rangle)^2 &= 0.125 & (|\Psi(V', H', L, R)^T \Psi_i\rangle)^2 &= 0.125 & (|\Psi(V', V', R, R)^T \Psi_i\rangle)^2 &= 0.125 & (|\Psi(V', V', L, L)^T \Psi_i\rangle)^2 &= 0.125 \end{aligned}$$

This analysis shows that quantum mechanics (QM) is in agreement with experimental results. The next step is to perform an experiment that shows that local realism (LR) is not in agreement with experimental results.

The fact that the eigenvalues of the individual operators examined above is +1, guarantees that the same is true for their product.

$$(x_1 x_2 x_3 x_4) (x_1 y_2 x_3 y_4) (x_1 x_2 y_3 y_4) = 1$$

Local realism assumes that physical properties exist independent of measurement. Because commuting operators have simultaneous eigenvalues $x_1 x_1 = x_2 x_2 = x_3 x_3 = y_4 y_4$. It follows that,

$$(x_1 y_2 y_3 x_4) = 1$$

The following results are consistent with this local realism analysis: H'RRH', H'RLV', H'LRV', H'LLH', V'RRV', V'RLH', V'LRH' and V'LLV'. As shown below, this is in complete disagreement with quantum mechanics and the experimental data. QM shows that the eigenvalue of the operator is actually -1, and, furthermore none of LR predicted results are observed. QM, however, is in agreement with the experimental results.

σ_{xyyx} experiment:

Operator:

$$\sigma_{xyyx} = \text{kroncker}(H'V', \text{kroncker}(RL, \text{kroncker}(RL, H'V')))$$

Eigenvalue/Expectation Value:

$$\Psi_i^T \sigma_{xyyx} \Psi_i = 1$$

Observed: H'H'RR, H'H'LL, H'V'RL, H'V'LR, H'V'RL, V'H'LR, V'V'RR and V'V'LL.

$$\begin{aligned} (|\Psi(H', R, R, V')^T \Psi_i\rangle)^2 &= 0.125 & (|\Psi(H', R, L, H')^T \Psi_i\rangle)^2 &= 0.125 & (|\Psi(H', L, R, H')^T \Psi_i\rangle)^2 &= 0.125 & (|\Psi(H', L, L, V')^T \Psi_i\rangle)^2 &= 0.125 \\ (|\Psi(V', R, R, H')^T \Psi_i\rangle)^2 &= 0.125 & (|\Psi(V', R, L, V')^T \Psi_i\rangle)^2 &= 0.125 & (|\Psi(V', L, R, V')^T \Psi_i\rangle)^2 &= 0.125 & (|\Psi(V', L, L, H')^T \Psi_i\rangle)^2 &= 0.125 \end{aligned}$$

Appendix

All four operators commute with each other allowing them to have simultaneous eigenvalues.

$$\begin{aligned} \sigma_{xxxx} \sigma_{xyxy} - \sigma_{xyxy} \sigma_{xxxx} &\rightarrow 0 & \sigma_{xxxx} \sigma_{xyyx} - \sigma_{xyyx} \sigma_{xxxx} &\rightarrow 0 & \sigma_{xxxx} \sigma_{xxyy} - \sigma_{xxyy} \sigma_{xxxx} &\rightarrow 0 \\ \sigma_{xxyy} \sigma_{xyxy} - \sigma_{xyxy} \sigma_{xxyy} &\rightarrow 0 & \sigma_{xxyy} \sigma_{xyyx} - \sigma_{xyyx} \sigma_{xxyy} &\rightarrow 0 & \sigma_{xyxy} \sigma_{xyyx} - \sigma_{xyyx} \sigma_{xyxy} &\rightarrow 0 \end{aligned}$$

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