Experimental Violation of the CHSH Bell Inequality

Michael Dapolito, Eric Wu, Christopher Ianzano, Samet Demircan

Department of Physics and Astronomy, Stony Brook University

History

1935: Einstein, Podolsky, and Rosen published a paper in which they proposed the use of local hidden-variables to circumvent the apparent violation of locality in quantum entanglement (known as the EPR paradox). Einstein was also discontent with the probabilistic nature of quantum theory.

1964: Physicist John S. Bell provided a mathematical formulation of locality and realism based on the existence of local hidden-variables and showed that it was not consistent with quantum theory. The formulation is an inequality that can be violated when applied to quantum systems, and thus demonstrates that local hidden-variable theories cannot predict all the possible outcomes of quantum mechanics.

CHSH Inequality

A popular form of Bell's inequality is the CHSH (John Clauser, Michael Horne, Abner Shimony, and Richard Holt) inequality. The CHSH inequality is defined by a parameter "S," where $|S| \leq 2$ and

$$S = E(\alpha,\beta) + E(\alpha',\beta) + E(\alpha,\beta') + E(\alpha',\beta)$$

The terms E(α,β) etc. are the expectation values of the product of the outcomes of the experiment. Each E(α,β) term is given by:

$$E(\alpha,\beta) = \frac{C(\alpha,\beta) - C(\alpha,\beta_\perp) - C(\alpha_\perp,\beta) + C(\alpha_\perp,\beta_\perp)}{C(\alpha,\beta) + C(\alpha,\beta_\perp) + C(\alpha_\perp,\beta) + C(\alpha_\perp,\beta_\perp)}$$

where C(α,β) is the number of coincidences for the specific configurations of polarizer angles α and β. Another important parameter is the visibility, V. This is defined from the maximum value of S: $S_{max} \leq 2\sqrt{2}V \Rightarrow V \leq 0.71$ and can be calculated using:

$$V = \frac{C_{max} - C_{min}}{C_{max} + C_{min}}$$

Generating Entangled Photon Pairs

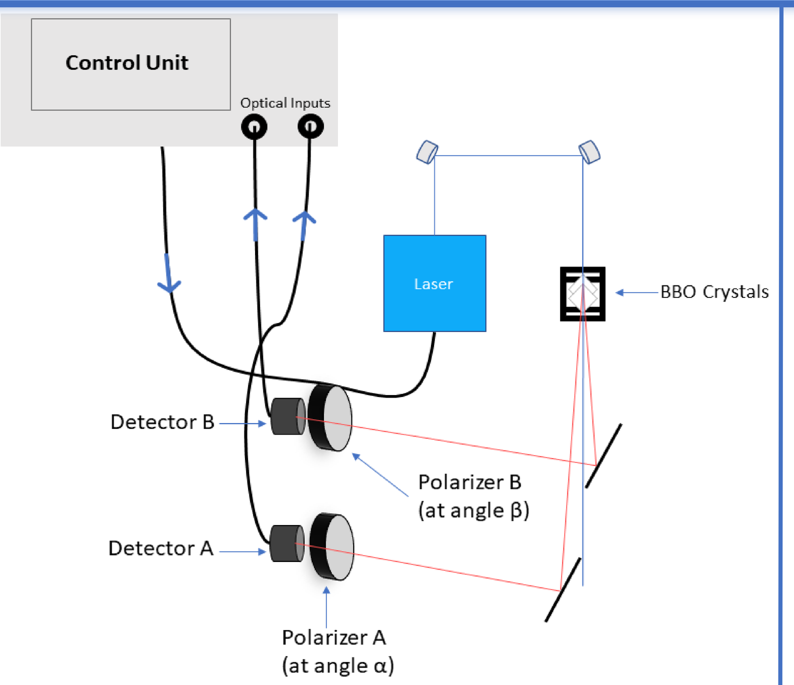

Figure 1: Schematic of the quED

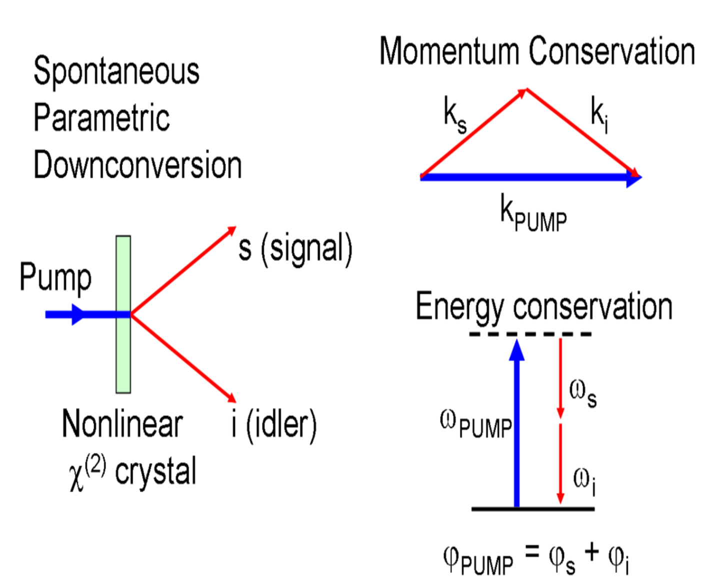

Figure 2: SPDC from a Type I BBO Crystal

This setup uses Type I BBO crystals to generate entangled photon pairs with the same polarizations. This process is also known as spontaneous parametric down-conversion (SPDC). SPDC is where, for example, a diagonally polarized photon gets down converted when passing through a BBO crystal and produces a pair of horizontally or vertically polarized photons. This can be expressed as:

$$\frac{1}{2}[|H\rangle + |V\rangle] \rightarrow \frac{1}{\sqrt{2}}[|HH\rangle + |VV\rangle]$$

Coincidence Counts

The control unit shown in Figure 1 is used to count and record the number of coincidences. A coincidence is defined as the simultaneous detection of an electric pulse at both photodetectors. The probability that two entangled photons will be simultaneously detected is:

$$P_{vv} = \frac{1}{2}\cos^2(\beta - \alpha)$$

In order to confirm a violation of the CHSH inequality, we plotted the coincidence counts as a function of β, incrementing β from 0° to 360° in steps of 10° while keeping α constant at 0°, 45°, 90° and 135°.

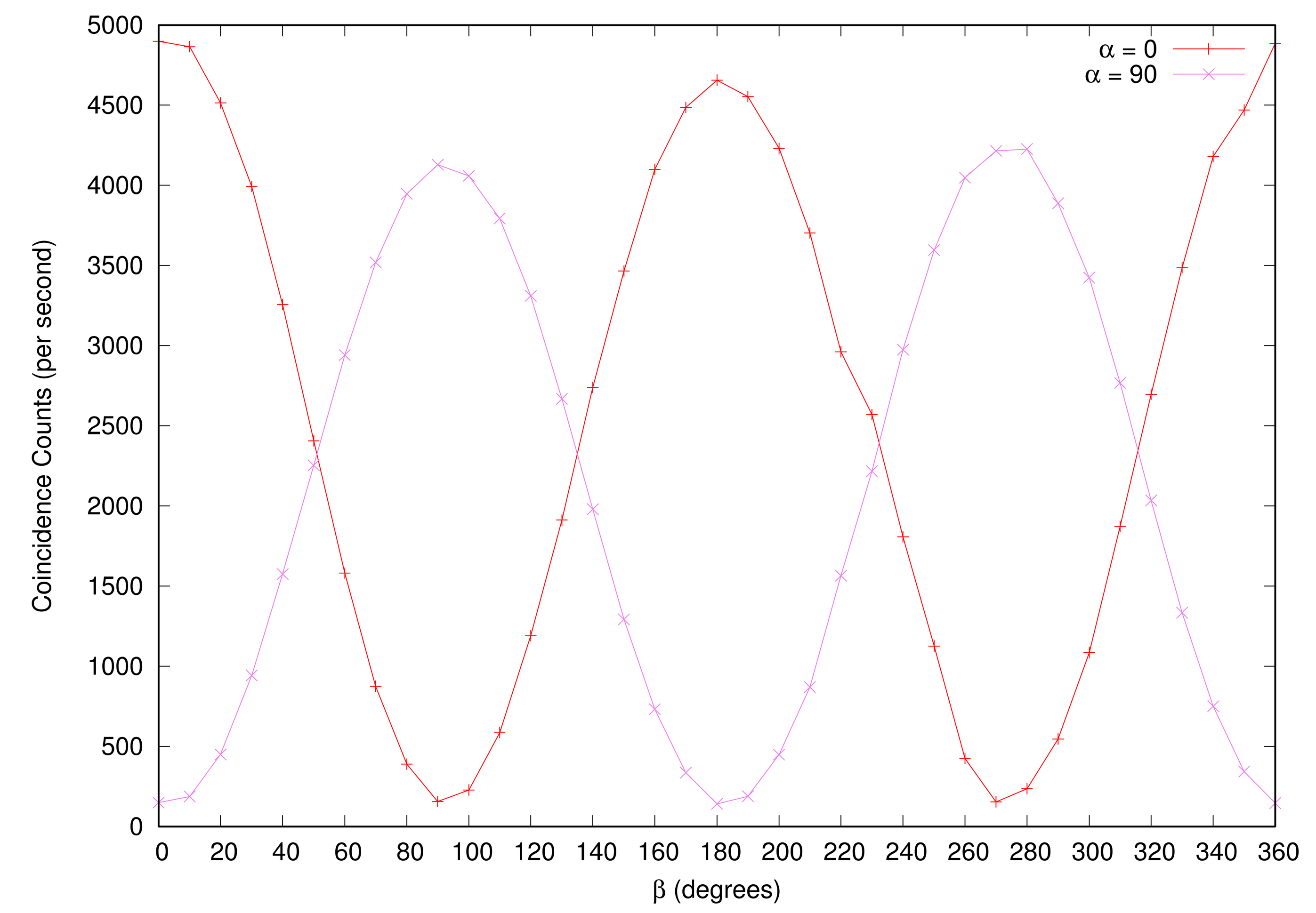

Figure 3: Coincidence counts vs. β when α is kept constant at 0° and 90°

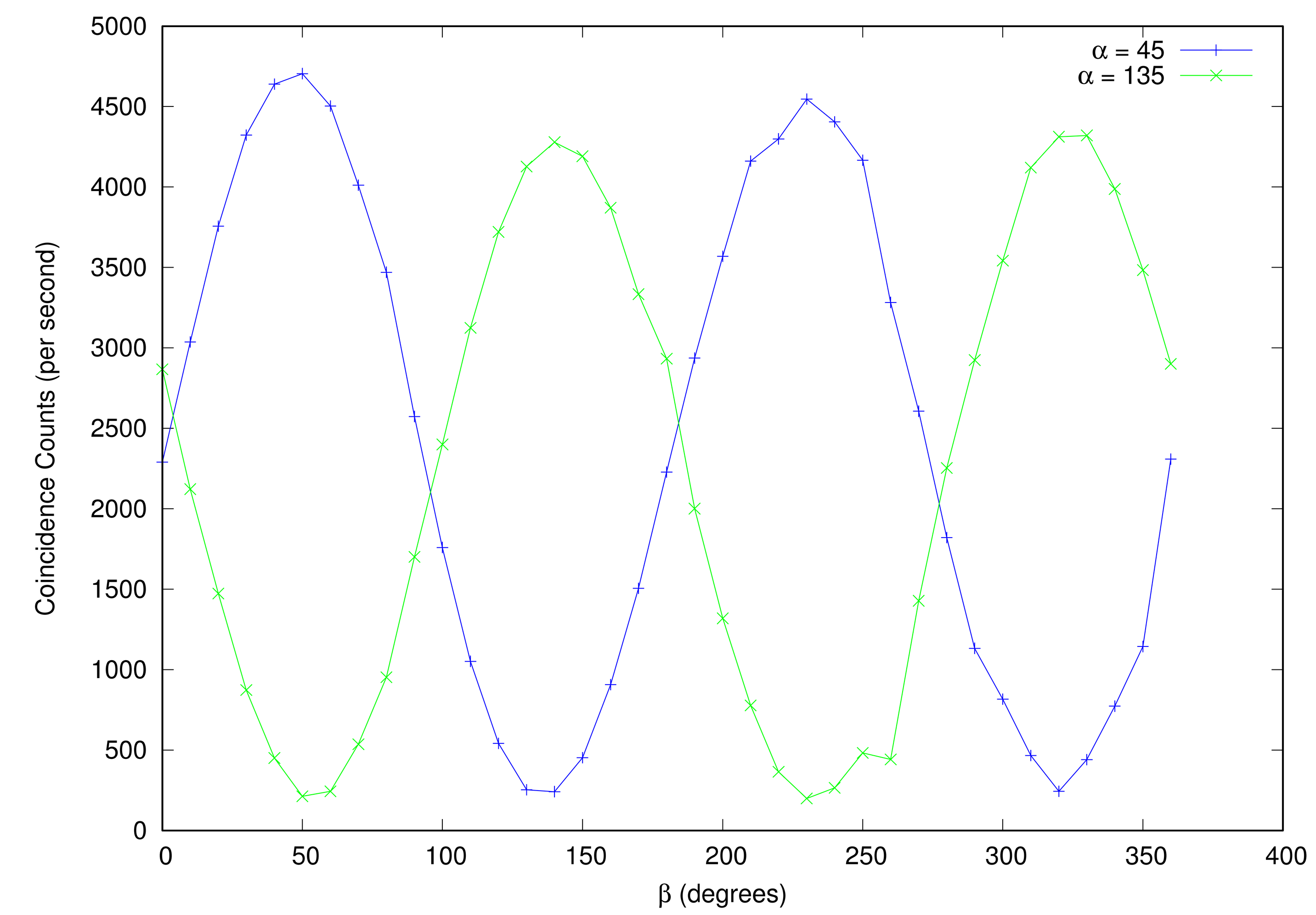

Figure 4: Coincidence counts vs. β when α is kept constant at 45° and 135°

Results

α	β	$C_{recorded}$	$C_{accidental}$	C_{net}
-45°	22.5°	1231	116	1115
-45°	67.5°	349	93	256
-45°	112.5°	2670	91	2579
-45°	157.5°	3356	313	3043
0°	22.5°	4095	142	3953
0°	67.5°	1066	117	949
0°	112.5°	672	115	557
0°	157.5°	3856	138	3718
45°	22.5°	3694	120	3574
45°	67.5°	3370	99	3271
45°	112.5°	534	97	437
45°	157.5°	860	118	742
90°	22.5°	463	96	367
90°	67.5°	2353	78	2275
90°	112.5°	2666	77	2589
90°	157.5°	664	93	571

Table 1: Coincidence counts for the angles at which there is a maximum violation of the CHSH inequality.

α	C_{max}	C_{min}	Visibility	σ_v
0°	4898	154	0.9389	0.0048
45°	4705	240	0.9026	0.0061
90°	4226	142	0.9350	0.0054
135°	4320	199	0.9118	0.0061

Table 2: Visibility measurements for α in the horizontal, vertical, and diagonal bases

Using the data from Table 1, we calculated **S = 2.696 ± 0.029**; a **36 σ** violation.

Conclusion

We have confirmed that the coincidence counts as a function of β follows a cosine squared relationship, the visibility is greater than 71%, and S is greater than two. Therefore, we have experimentally verified a violation of Bell's inequality by 36 standard deviations.

This experiment was done to maximize the extent to which the CHSH inequality can be violated and highlight the stark contrast between classical and quantum mechanics. This contrast had far reaching philosophical implications for 20th century physicists. The debate as to how quantum theory should be interpreted was not settled until 29 years after the EPR paradox was first published and it was done so with a relatively simple mathematical formulation.

References and Acknowledgements

[1] A. Einstein, B. Podolsky, and N. Rosen. Physical Review 47, 777 (1935)
[2] J. Bell, Physics 1, 195 (1964)
[3] J. Clauser, M. Horne, A. Shimony, and R. Holt, Physics Review Letters 23, 880 (1969)
[4] qutools. v.1.4 (2013). Entanglement Demonstrator: User's and Operation Manual

Supported by Simons Foundation and ONR