**Quantum Lab #1: Polarization Entanglement – Violating Bell’s Inequality**

***References***:

A.P. French and E.F. Taylor, An Introduction to Quantum Physics, Chapter 6

J.F. Clauser and A. Shimony, Bell’s theorem: experimental tests and implications, Rep. Prog. Phys., Vol. 41, 1978.

***Motivation***

The physics of systems at the quantum scale differs from the physics of systems on the classical scale. This fact is easily highlighted by comparing, for example, the motion of a baseball to that of an electron. The classical trajectory of a baseball can be completely characterized and determined in time by measuring its position and momentum. On the other hand, because of the Heisenberg uncertainty principle, it is not possible to simultaneously measure both the position and momentum of a quantum particle. Instead, the trajectory of a quantum particle is a probabilistic entity. Quantum physics is a probabilistic theory implying that quantities such as position or momentum can only be known after a measurement takes place. Before a measurement, a particle or system of particles exists in a spectrum of states defined by some probability density function. A measurement of a quantum system will yield a specific value that is consistent with the predicted measurement probabilities.

Even more interesting is the fact that quantum mechanics allows for entangled states. This means that a system of two particles can be preconfigured to exist in a condition where the measurement of the state of one particle is tied to the state of the other particle regardless of the spatial and temporal separation between the particles. This means the quantum mechanics is both a non-deterministic and non-local theory. Combining the concepts of quantum probabilistic measurement and entanglement leads to behaviors that troubled many who played a role in the inception of the quantum theory. The goal of this lab to explore and verify such non-local and non-deterministic behaviors.

Even though, by 1930, modern quantum theory was well-established and empirically verified in a number of different ways, there were still many who opposed its probabilistic formulation and its non-local implications. Einstein, in particular, was troubled that information between two particles could be shared instantly across any distance, thus violating his theory of special relativity. There were many attempts to formulate local, deterministic theories (often referred to as ‘hidden variable theories’) that could reproduce these results of quantum mechanics, with some minimal successes. By 1969, the ability to determine which theory (hidden variable or quantum theory) is the more accurate description of nature was developed by John S. Bell. Bell’s theorem and its refinements consider experimental setups involving entangled particles and prove that no local, deterministic theory can recover the results predicted by quantum mechanics. In other words, a Bell test can quantify that quantum entanglement exists, and that hidden variables cannot explain the instantaneous transmission of information between quantum particles.