Quantum Entanglement at Kenyon College

Constructing an Entanglement Apparatus for the Undergraduate Laboratory

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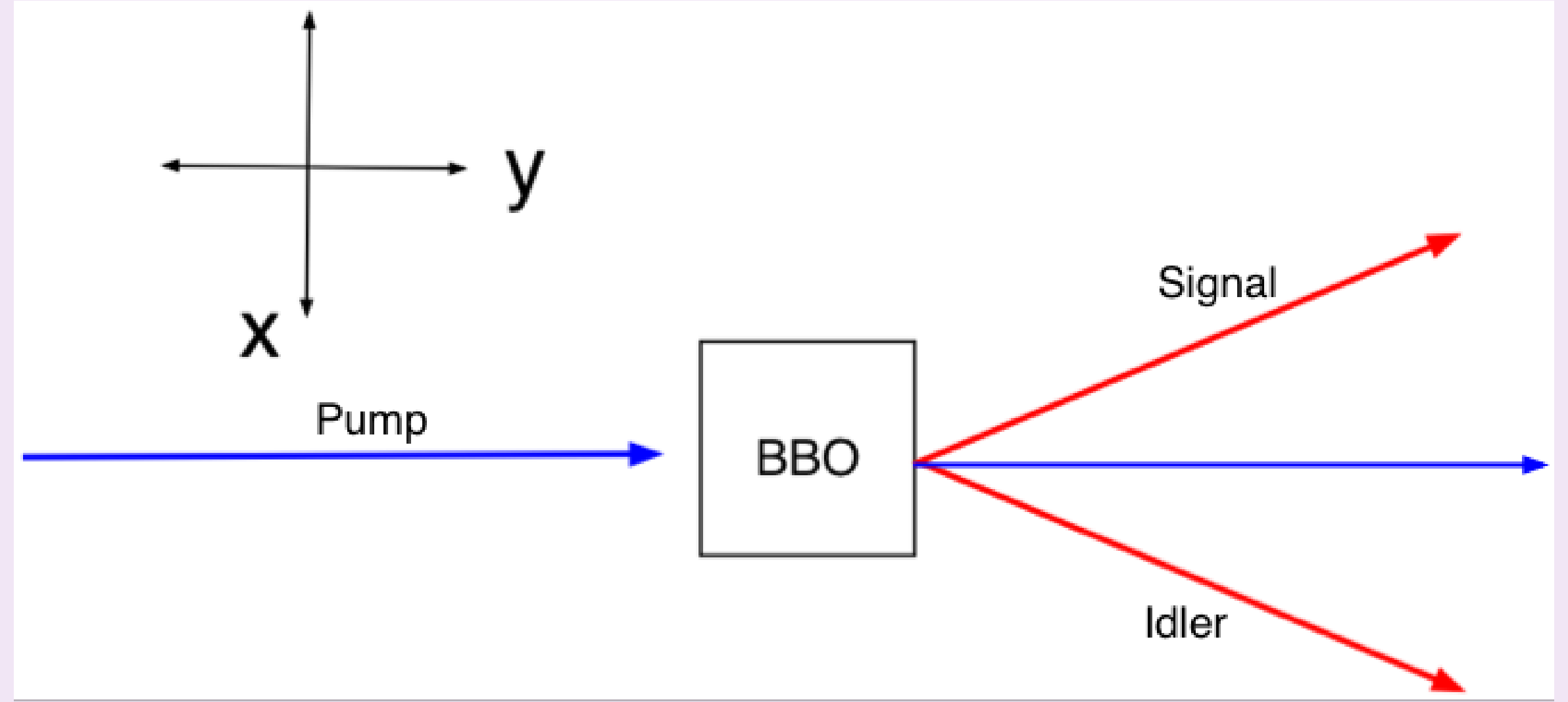
Abstract

Modern quantum entanglement research is limited to mostly large research institutions, but given access to specific equipment, it is possible for an undergraduate laboratory to construct a quantum entanglement apparatus. "High-quality" light of wavelength approximately equal to 405nm sent through a non-linear BBO crystal will undergo spontaneous parametric down conversion into infrared light of comparable quality. This process produces pairs of these down-converted photons which exit the crystal such that their net directionality is consistent with the conservation of energy. The result is an excellent source of entangled photons, because the photons are polarization correlated as a result of the down-conversion.

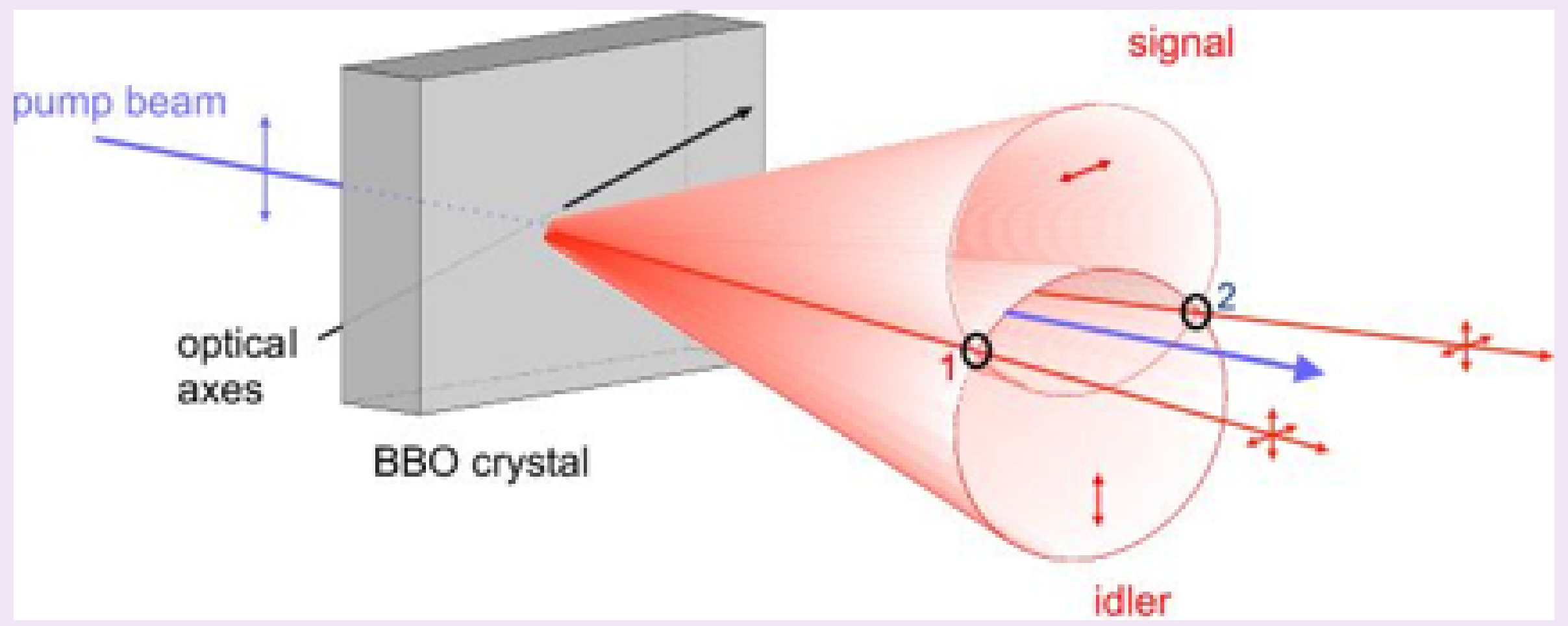
What is Entanglement?

An entangled state is a composite state for which "it is not possible to assign state vectors to the individual subsystems."

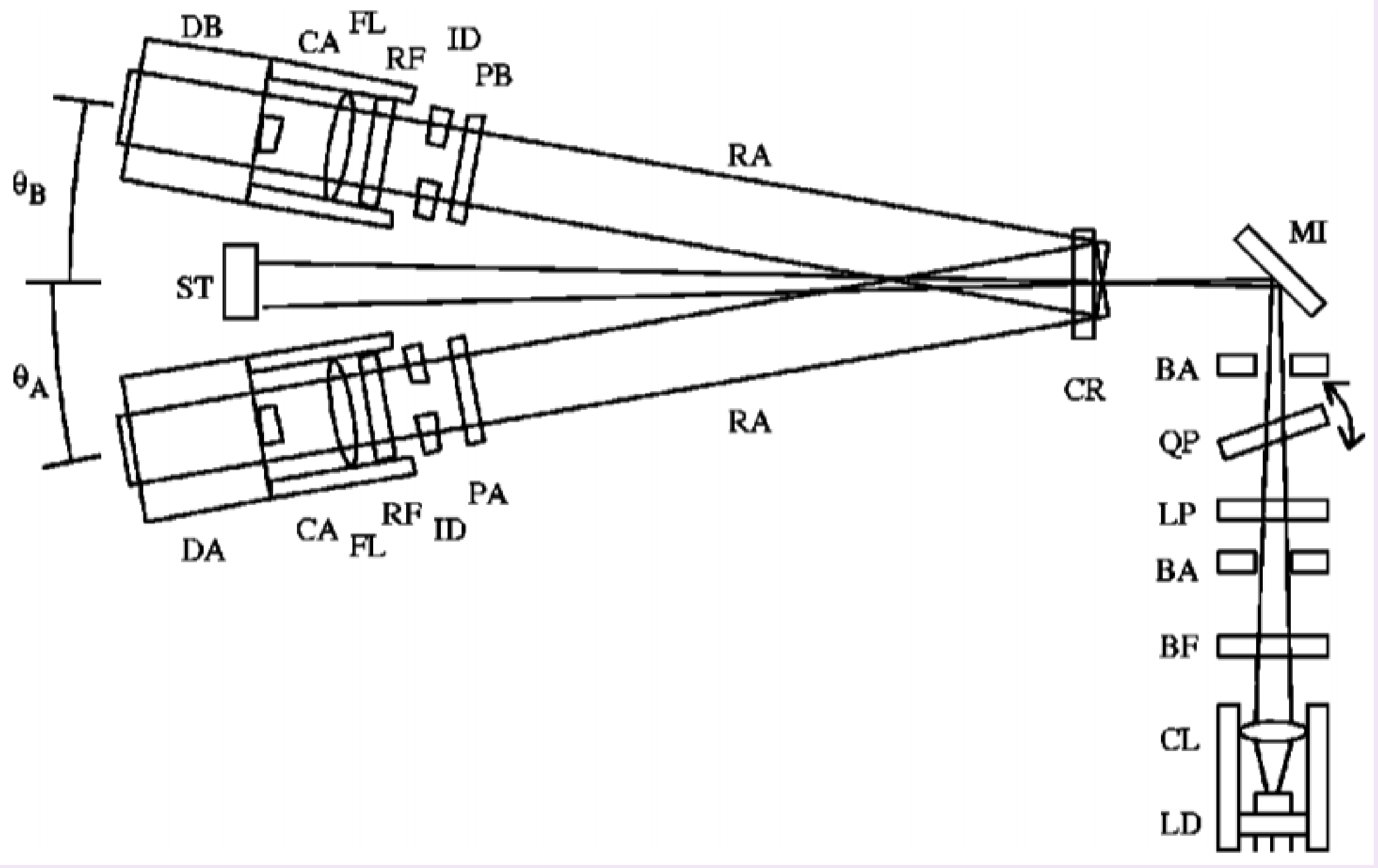
Spontaneous Parametric Downconversion



Inside a type-II beta Barium Borate crystal, photons of wavelength approximately equal to 400nm are spontaneously down-converted into pairs of infrared photons. Each pump photon is converted into a signal and idler photon, which together conserve the momentum and energy of the pump.



The Set-up



Light from a commercial diode laser, $\boldsymbol{\lambda} = 404$nm, passes through a BBO crystal where it is down-converted into cones of infrared light. The intersections of these cones is picked out by the height of the detectors, and we sweep through angles in an attempt to maximize the observed count rates. We are interested primarily in the degenerate case.

The Math

Consider the (physically-realizable) composite state,

$$|\boldsymbol{\Psi}_{1,2}\rangle = \frac{1}{\sqrt{2}}(|\updownarrow_1\updownarrow_2\rangle + |\leftrightarrow_1\leftrightarrow_2\rangle)$$

We're going to show that this is an entangled state:

$$\frac{1}{\sqrt{2}}(|\updownarrow_1\updownarrow_2\rangle + |\leftrightarrow_1\leftrightarrow_2\rangle) \neq |\psi_1\rangle \otimes |\phi_2\rangle$$

We proceed by contradiction. Assume:

$$|\boldsymbol{\Psi}_{1,2}\rangle = \frac{1}{\sqrt{2}}(|\updownarrow_1\updownarrow\ 2\rangle + |\leftrightarrow_1\leftrightarrow_2\rangle) = |\psi_1\rangle \otimes |\phi_2\rangle$$

By the distributivity of the product operation,

$$|\boldsymbol{\Psi}_{1,2}\rangle = |\psi_1\rangle \otimes |\phi_2\rangle = \alpha\gamma\,|\updownarrow_1\updownarrow_2\rangle + \alpha\delta\,|\updownarrow_1\leftrightarrow_2\rangle + \beta\gamma\,|\leftrightarrow_1\updownarrow_2\rangle + \beta\delta\,|\leftrightarrow_1\leftrightarrow_2\rangle$$

So, we have,

$$\frac{1}{\sqrt{2}}(|\updownarrow_1\updownarrow_2\rangle + |\leftrightarrow_1\leftrightarrow_2\rangle) = \alpha\gamma\,|\updownarrow_1\updownarrow_2\rangle + \alpha\delta\,|\updownarrow_1\leftrightarrow_2\rangle + \beta\gamma\,|\leftrightarrow_1\updownarrow_2\rangle + \beta\delta\,|\leftrightarrow_1\leftrightarrow_2\rangle$$

$\alpha = 0, \delta = 0, \beta = 0, \gamma = 0 \Rightarrow$ Contradiction. Therefore,

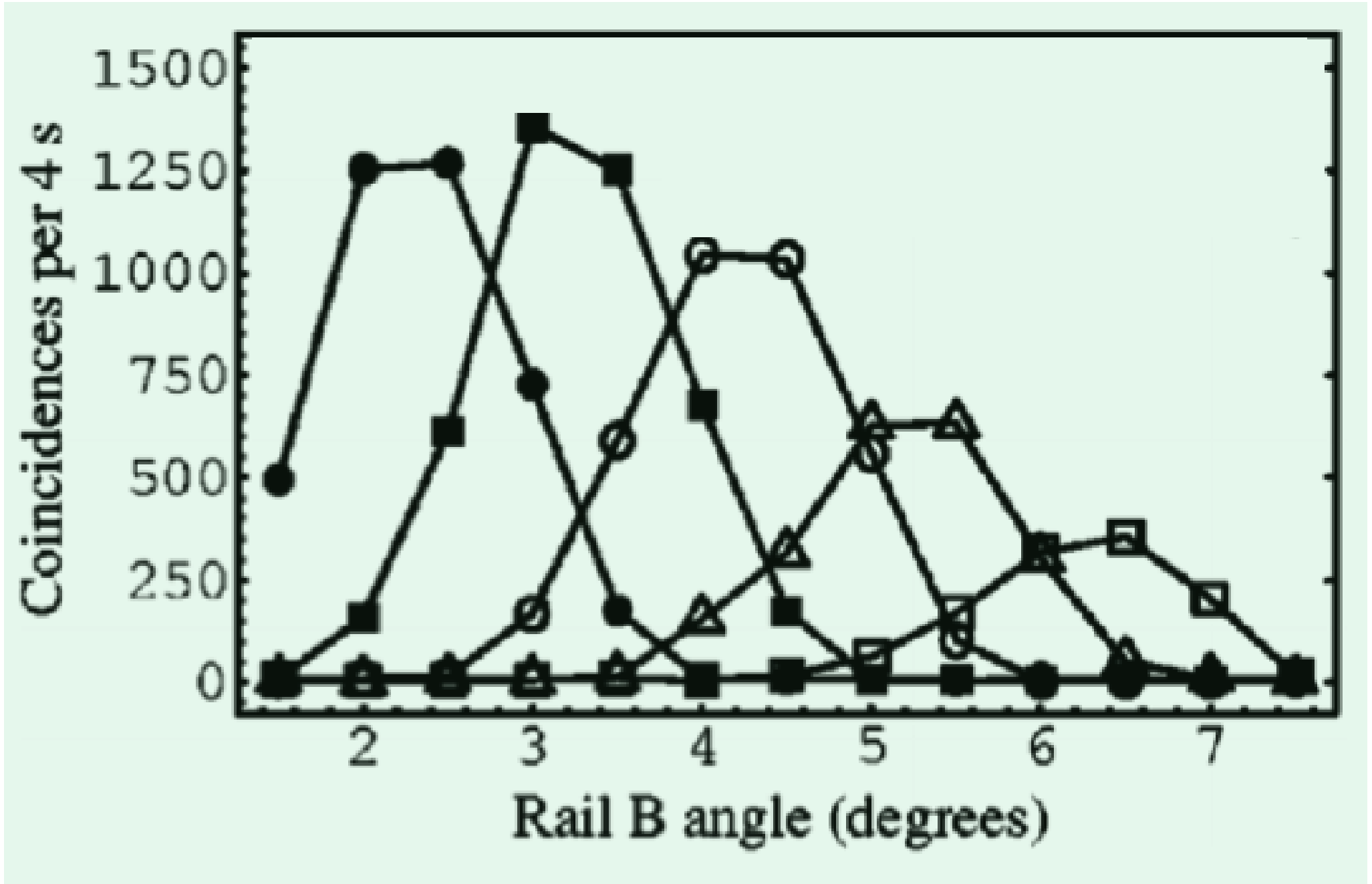
$$|\boldsymbol{\Psi}_{1,2}\rangle \neq |\psi_1\rangle \otimes |\phi_2\rangle = \alpha\gamma\,|\updownarrow_1\updownarrow_2\rangle + \alpha\delta\,|\updownarrow_1\leftrightarrow_2\rangle + \beta\gamma\,|\leftrightarrow_1\updownarrow_2\rangle + \beta\delta\,|\leftrightarrow\ 1\ \leftrightarrow_2\rangle$$

Background

The earliest manifestation of quantum entanglement is given to us from Einstein Podolsky, and Rosen in their 1935 paper titled "Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?" This question prompted thought experiments by prominent physicists in the coming decades, and since that time, experimental techniques have been thoroughly developed which have proved that entanglement exists.

Early in the Spring, the Physics department acquired the final pieces of equipment necessary to construct such an apparatus, namely single photon detectors. The task I set out with at that time was to construct the infrastructure necessary to run a cavity to produce the quality of light needed for the down-conversion process as well as the hardware to allow the detectors to count coincident pairs of entangled photons. The focus of the project eventually shifted entirely detection set-up, and a commercial diode laser was purchased as a substitute for the cavity

The Plan



My primary intention is to thoroughly prove that I have produced entangled photons through a series of diagnostic experiments, as well as traditional entanglement experiments such as Bell's Inequalities and Ghost Interference. At the end of this process, I intend to leave a fully functional entanglement apparatus to be used for future student research.

References

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