A5.3. The Polarization of Photons.

A photon is the name given to a 'piece' of light. In this treatment, where it is argued (see Part II) there is no evidence for particles, it refers to a wave function/state vector with mass 0, spin 1, and charge 0. Each photon (photon wave function) travels at the speed of light. If it has wavelength λ, its energy is hc/λ and its momentum is h/λ where *c* is the speed of light and *h* is Planck's constant.

Two states of polarization.

Each photon has two possible states of *polarization*, which is analogous to spin or angular momentum. This can be visualized in the following way: A photon can be thought of (at least classically) as consisting of oscillating electric and magnetic fields. If a photon is traveling in the z direction, its electric field can either oscillate in the x direction, so the photon is represented by $|x\rangle$, or its electric field can be oscillating in the y direction, so it is represented by $|y\rangle$ (see A6.2 on the ket notation).

If it is traveling in the z direction, it can also be polarized so its electric field oscillates in any direction in the x-y plane, say at an angle θ to the x axis. In that case, the photon state can be represented as a (linear) combination of the $|x\rangle$ and $|y\rangle$,

$$|ph,\theta\rangle = \cos(\theta)|x\rangle + \sin(\theta)|y\rangle \tag{1}$$

Circular polarization.

The states where the polarization is along either the x-axis or along the y-axis are *linearly* polarized. Whereas the states

$$|R\rangle = [|x\rangle + i|y\rangle]/\sqrt{2} \tag{2}$$
$$|L\rangle = [|x\rangle - i|y\rangle]/\sqrt{2}$$

are called *circularly* polarized.

Group representation theory.

The two states of polarization are analogous to spin states. The photon has spin 1 so that if it had non-zero mass, it would have three spin states, 1, 0, – 1. But since it has zero mass, the 0 spin state, along the z-axis if it is traveling in that direction, is missing.

Probability and polarization states.

There are certain materials (such as Polaroid) that act as filters in that they let through only that part of the photon polarized in a certain direction. In terms of the wave function, if we have a polarizer $[P(x)]$ that lets through only $|x\rangle$ photons, then we have, for a photon polarized at an angle θ to the x-axis,

$$[P(x)]\,(\cos(\theta)|x\rangle + \sin(\theta)|y\rangle) = \cos(\theta)|x\rangle \tag{3}$$

What this translates into experimentally is the following: Suppose we have a beam of light in state Eq. (1) that contains N photons crossing a given plane per sec, each moving at the speed of light. Then a 100% efficient detector put in the beam will record N 'hits' per second. But if we put an *x* polarizer in the beam, the detector will record only $N\cos^2(\theta)$ hits per second. And if we put in a *y* polarizer, the detector will record only $N\sin^2(\theta)$ hits per second.

Thus the polarization state of Eq. (1) appears from the equation to be composed of both a photon polarized in the *x* direction, $|x\rangle$, *and* a photon polarized in the *y* direction, $|y\rangle$. But if we measure, we find *either* an $|x\rangle$ photon, on a fraction $\cos^2(\theta)$ of the measurements, *or* a $|y\rangle$ photon, on a fraction $\sin^2(\theta)$ of the measurements. (See also Ch. 8). Not so easy to understand!

Polarization states and separate universes.

There are crystals that can separate the photon into its *x* and *y* polarization parts, so that the *x* polarized part travels on one path and the *y* polarized part travels on another path. One can put a detector in each path, and one can have an observer that looks at each detector. If we send a single photon, in the state of Eq. (1), through this apparatus, the wave function of the two detectors plus the observer is still a sum of just two terms:

$$|\text{state}\rangle = \cos(\theta)|x\rangle|\text{Det}(x),\text{yes}\rangle|\text{Det}(y),\text{no}\rangle|\text{Obs sees x,yes; y,no}\rangle + \sin(\theta)\,|y\rangle|\text{Det}(x),\text{no}\rangle|\text{Det}(y),\text{yes}\rangle|\text{Obs sees x,no; y,yes}\rangle \quad (4)$$

But now the whole 'universe'—photon, detectors and observer—has split into two states. In particular, if you are the observer, there are two *versions* of you! On a fraction $\cos^2(\theta)$ of the runs, the "*x*, yes; *y*, no" version will correspond to your perceptions and on a fraction $\sin^2(\theta)$ of the runs the "*x*, no; *y*, yes" version will correspond to your perceptions. On a given run, quantum mechanics does not say which version will correspond to your perceptions. So this experiment and the state of Eq. (4) give another example (in addition to that of Ch. 6) of quantum mechanics presenting us with two versions of reality—one version of you perceiving polarization *x and, at the same time,* another version of you perceiving polarization *y*.