Fig. 8A-5
Schematic diagram of a calcite analyzer. In this orientation the device is called an xy analyzer.
11–4 The polarization states of the photon

There are a number of other two-state systems which are interesting to study, and the first new one we would like to talk about is the photon. To describe a photon we must first give its vector momentum. For a free photon, the frequency is determined by the momentum, so we don’t have to say also what the frequency is. After that, though, we still have a property called the polarization. Imagine that there is a photon coming at you with a definite monochromatic frequency (which will be kept the same throughout all this discussion so that we don’t have a variety of momentum states). Then there are two directions of polarization. In the classical theory, light can be described as having an electric field which oscillates horizontally or an electric field which oscillates vertically. (For instance), these two kinds of light are called x-polarized and y-polarized light. The light can also be polarized in some other direction, which can be made up from the superposition of a field in the x-direction and one in the y-direction. Or if you take the x- and the y-components out of phase by 90°, you get an electric field that rotates—the light is elliptically polarized. (This is just a quick reminder of the classical theory of polarized light that we studied in Chapter 35, Vol. I.)

Now, however, suppose we have a single photon—just one. There is no electric field that we can discuss in the same way. All we have is one photon. But a photon has to have the analog of the classical phenomena of polarization. There must be at least two different kinds of photons. At first, you might think there should be an infinite variety—after all, the electric vector can point in all sorts of directions. We can, however, describe the polarization of a photon as a two-state system. A photon can be in the state \( |x\rangle \) or in the state \( |y\rangle \). By \( |x\rangle \) we mean the polarization state of each one of the photons in a beam of light which classically is x-polarized light. On the other hand, by \( |y\rangle \) we mean the polarization state of each of the photons in a y-polarized beam. And we can take \( |x\rangle \) and \( |y\rangle \) as our base states of a photon of given momentum pointing at you—in what we will call the z-direction. So there are two base states \( |x\rangle \) and \( |y\rangle \), and they are all that are needed to describe any photon at all.

For example, if we have a piece of polaroid set with its axis to pass light polarized in what we call the x-direction, and we send in a photon which we know is in the state \( |y\rangle \), it will be absorbed by the polaroid. If we send in a photon which we know is in the state \( |x\rangle \), it will come right through as \( |x\rangle \). If we take a piece of calcite which takes a beam of polarized light and splits it into an \( |x\rangle \) beam and a \( |y\rangle \) beam, that piece of calcite is the complete analog of a Stern-Gerlach apparatus which splits a beam of silver atoms into the two states \( |+\rangle \) and \( |-\rangle \). So every-
The classical picture and the quantum picture give similar results. If you were to throw 10 billion photons at the second polaroid, and the average probability of each one going through is, say, 3/4, you would expect 3/4 of 10 billion would get through. Likewise, the energy that they would carry would be 3/4 of the energy that you attempted to put through. The classical theory says nothing about the statistics of the thing—it simply says that the energy that comes through will be precisely 3/4 of the energy which you were sending in. That is, of course, impossible if there is only one photon. There is no such thing as 3/4 of a photon. It is either all there, or it isn’t there at all. Quantum mechanics tells us it is all there 3/4 of the time. The relation of the two theories is clear.

What about the other kinds of polarization? For example, right-hand circular polarization? In the classical theory, right-hand circular polarization has equal components in x and y which are 90° out of phase. In the quantum theory, a right-hand circularly polarized (RHC) photon has equal amplitudes to be polarized |x⟩ or |y⟩, and the amplitudes are 90° out of phase. Calling a RHC photon a state |R⟩ and a LHC photon a state |L⟩, we can write (see Vol. I, Section 33–1)

\[
|R⟩ = \frac{1}{\sqrt{2}} (|x⟩ + i |y⟩),
\]

\[
|L⟩ = -\frac{1}{\sqrt{2}} (|x⟩ - i |y⟩).
\]

(11.34)