12.6: Entangled Particles

When two particles' quantum state is a combined quantum state, we say that those two particles are entangled. Most of the time we encounter such states, we don't worry about it too much. The two electrons in the ground state of Helium have entangled states, because they are indistinguishable particles. You can't talk about the state of one electron without talking about the state of another.

Entangled quantum states become more interesting when you separate the two particles. Suppose that there is some sort of reaction that produces two electrons that have a total spin angular momentum of zero. We've seen before that the state of these two electrons is then:

$$\frac{1}{\sqrt{2}}\left|+z_1\right\rangle\left|-z_2\right\rangle-\frac{1}{\sqrt{2}}\left|+z_2\right\rangle\left|-z_1\right\rangle \tag{12.20}$$

Although the total z angular momentum of this combined state is 0, a definite value, the angular momentum of an individual electron is not in a definite state. Now suppose that you separate these two electrons; it may be that the reaction that produces them sends them shooting off in two directions, which for discussion purposes we shall call "left" and "right".

Now let's suppose that somebody far off to the left detects the left electron and measures its z-spin. This measurement will collapse the wave function of the left electron, putting it into a state of definite z spin. However, because it's a combined state for the two electrons, you can't collapse the wave function of just one of them; you have to collapse the entire state all at once. Therefore, if somebody measures the z spin of the left electron, the wave function of the right electron also collapses at that moment, even if nobody has made a measurement on it. If the left observer measures that the left electron is spin up, then anybody off to the right will observe that the right electron is spin down; the right electron is no longer in an indefinite state, even though nothing was done to it.

This behavior of entangled particles is what Einstein referred to as "spooky action at a distance". (citation needed.) Not only was he disturbed by the stochastic nature √ of quantum mechanics, he was also bothered by what seemed to be communication faster than the speed of light. Does some sort of signal traverse from one electron to the other electron in order to communicate the fact that their mutual wave function has collapsed? Together with two other physicists, Podolsky and Rosen, Einstein argued that this behavior indicated that quantum theory had to be incomplete. In 1935, they published a paper describing what is now known as the "EPR Paradox" (Einstein et al., 1935). If quantum mechanics is indeed incomplete, then there would need to be some sort of "local hidden variable" that tells a particle which way its wave function should collapse when that particle is measured. This variable is "hidden" because it is not accounted for in quantum mechanics. In the early 1960's, physicist John Bell proposed experiments that would test the EPR paradox by being able to tell the difference between the standard predictions of quantum mechanics and the predictions of a theory that had some sort of local hidden variables (citation needed). √ Experiments performed since then have shown that in fact standard quantum mechanics does predict the correct results, and that therefore there are no local hidden variables. The fact is that, somehow, the wave function of an electron can collapse when another electron is measured— and that other electron may, at least in principle even if this is not realizable in practice, be light-years away. This raises philosophical issues associated with the interpretation of quantum mechanics, but also indicates that quantum mechanics remains a very robust theory.