Entanglement

Multi-particle entanglement is a process of interference that occurs when two or more particles exist in a superposition. Additionally, a single particle with multiple entangled degrees of freedom also can constitute an entangled state. For example, entanglement can be created within a single particle via both the particle's internal degrees of freedom and motional degrees of freedom. We will now further illustrate examples of entangled multi-particle states.

Entanglement via Mirror Recoil

A method that can be used to create an entangled multiparticle superposition is to utilize the beam splitter and the mirrors in Figure 2.2. There are two variations on Figure 2.2 that we will consider.

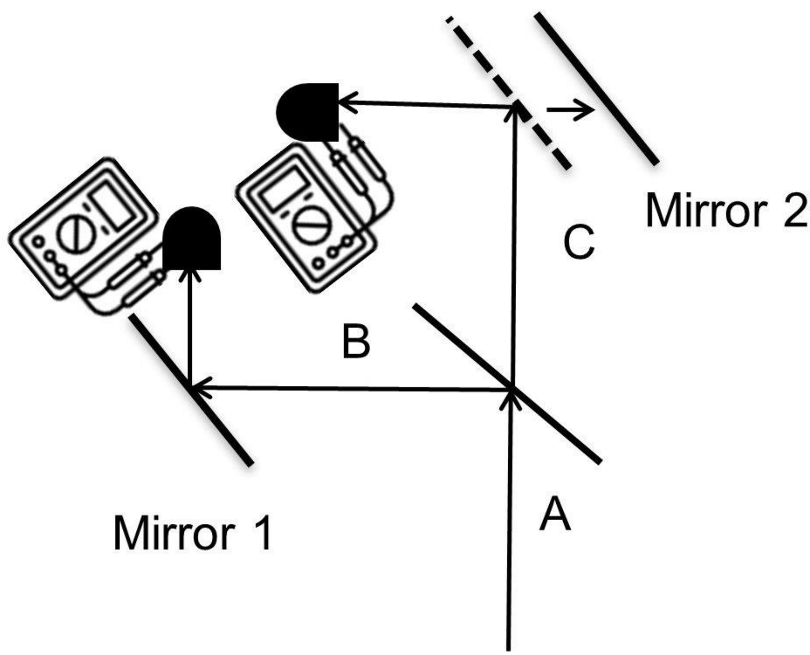

Figure 2.5: Single photon sent into a configuration of mirrors with momentum recoil of a mirror resulting in superpositions of its position.

In the first variation on creating an entangled multiparticle superposition, one could replace the heavy mirrors with a very light microscopic atomic mirror that significantly recoils when a photon is reflected by the mirror for which the situation that unitarily results is a superposition of the mirror position, as seen in Figure 2.5. Let the initial resting state of a mirror be denoted by $|\text{rest}\rangle$ and the recoiled state by $|\text{recoil}\rangle$. After being reflected by the mirrors, the state of the mirrors and the photon in

Paths B and C is given by:

$$|\Psi\rangle = \frac{1}{\sqrt{2}}\big(|\text{rest}\rangle_{\text{Mirror }B}|\text{recoil}\rangle_{\text{Mirror }C}|0\rangle_{\text{Photon,B}}|1\rangle_{\text{Photon,C}} + |\text{recoil}\rangle_{\text{Mirror }B}|\text{rest}\rangle_{\text{Mirror }C}|1\rangle_{\text{Photon,B}}|0\rangle_{\text{Photon,C}}\big).$$

As can be seen, the state $|\Psi\rangle$ involves a macroscopic superposition of a mirror. This becomes physically possible as long as the mirror is sufficiently microscopic and light so that the recoiled mirror is distinguishable from the initial state of the mirror at rest.

In the second variation of creating an entangled multiparticle superposition, we replace the output of the B and C ports of the beam splitter by a maximally entangled state of a sufficiently large number of photons that can impart a substantial momentum on not simply a microscopic mirror, but a macroscopic mirror. Such photon states, called NOON states [16] [17], are given by $|\psi\rangle = (|N\rangle|0\rangle + |0\rangle|N\rangle)/\sqrt{2}$. NOON states would be genuinely macroscopic superpositions for $N \to \infty$, though so far, they have been generated in optics or atoms only for low N [18]. When such a state of sufficiently high N impinges on mirrors, even macroscopic mirrors, the final state is entangled:

$$|\Psi\rangle = \frac{1}{\sqrt{2}}\big(|\text{rest}\rangle_{\text{Mirror }B}|\text{recoil}\rangle_{\text{Mirror }C}|0\rangle_{\text{Photon,B}}|N\rangle_{\text{Photon,C}} + |\text{recoil}\rangle_{\text{Mirror }B}|\text{rest}\rangle_{\text{Mirror }C}|N\rangle_{\text{Photon,B}}|0\rangle_{\text{Photon,C}}\big).$$

This approach can clearly be extended indefinitely via *nested interferometry* [19] allowing the superpositions to grow without limit, Figure 2.6.

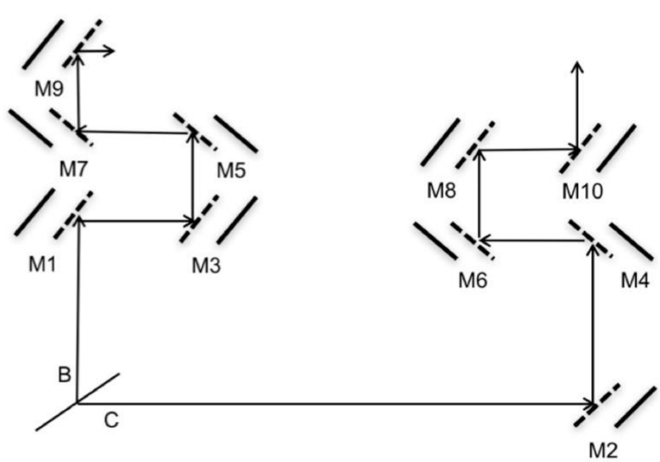

Figure 2.6: The single photon sent within a configuration of recoiling mirrors can clearly be extended indefinitely allowing the superpositions to grow without limit.