

Building a quantum system in Quantum Composer

Part IV: Tunnelling

4 Quantum tunnelling

4.1 What is tunnelling?

Tunnelling is a purely quantum phenomenon. We have a particle in a potential well, separated from an adjacent well by a barrier. Crucially, the height of the barrier is higher than the energy of the particle. Classically, you should have no chance at all of finding the particle on the other side of the barrier. In quantum mechanics, however, the wave function penetrates the barrier, and there is some probability density on the other side. It's as if, rather than going *over* the barrier, the particle has dug a tunnel *through* it. Figure 1 illustrates the effect of tunnelling in a two-well system.

Tunnelling is important. In living cells (including those from which you are made), there are organelles called mitochondria that respire, that is they turn the sugars you consume into energy in a form that can be used by the cell. Plant cells additionally have chloroplasts, which turn carbon dioxide in the air into the sugars that you later consume. Now, biochemical systems called *electron transport chains* (ETCs) are key to both of these processes. In an ETC, a high-energy electron moves between large protein complexes that float around in the membranes of mitochondria and chloroplasts from a source to a destination. (Plastoquinone, a key molecule in the photosynthetic ETC, is shown in Figure 2.) Think about each protein as a potential well; when the electron is transferred, it tunnels through the sides of the well. So tunnelling is needed for the fundamental processes of life.

Tunnelling also has quite a few engineering applications. Flash memory, used in USB flash drives and some computers, is based on tunnelling. It involves adding or removing electrons from a potential well inside a component called a transistor. This, in turn, changes the voltage required for the transistor to conduct electricity. Thus we may store store information.

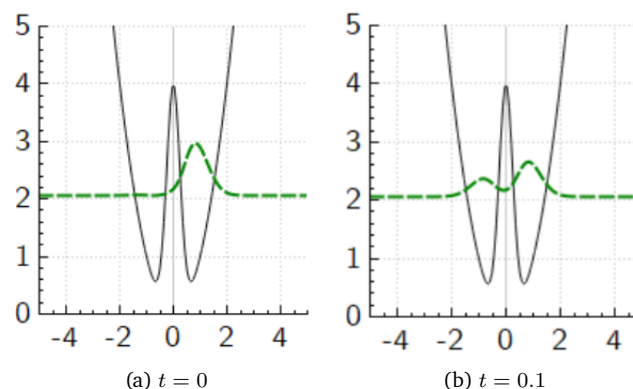


Figure 1: An illustration of the effect of tunnelling on a wave function. While at first there is no probability density in the left hand well, over time the probability density on the left increases, while the probability density on the right decreases.

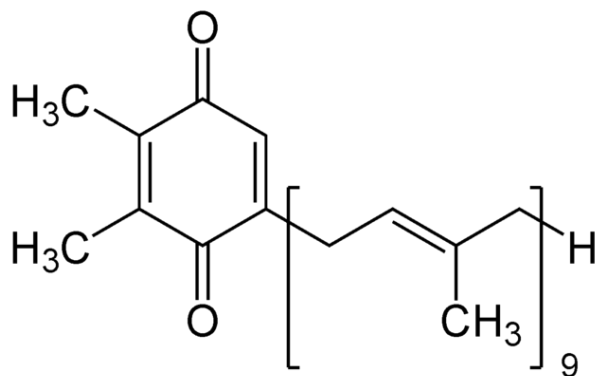


Figure 2: Plastoquinone is one of the molecules that carrier electrons between protein complexes in photosynthesis. It is a biological potential well. [Image: Yikrazuul / Wikimedia Commons]

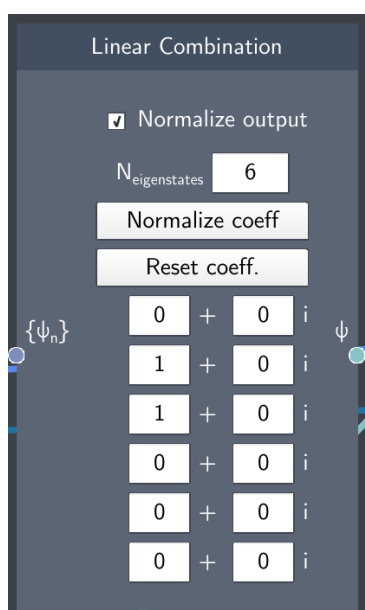


Figure 3: The **Linear Combination** box.

4.2 Investigating the conditions for tunnelling

Open the file `Exercise3.flow` in *Quantum Composer*. There are three graphs, as before, but now there are two variables to adjust. **Barrier** controls the height of an energy barrier between the two wells, and **Tilt** controls the relative tilt of the two wells.

- Introduce a barrier into the harmonic oscillator by changing the value of **Barrier**. Now it is set to 0, change it to 1, 2 and 3 consecutively. What happens to the energy states?
- Now set **Barrier** to 3. Try to create an equal superposition of the first two states such that the linear combination is present only in the right hand well. Press play to observe its time evolution. Do you see tunnelling?
- Increase the barrier height a lot, to 10. How does the time evolution change? Do you see tunnelling now?
- From what you have learned about tunnelling, formulate two conditions required for tunnelling.

Now we investigate the effects of tilting the wells. At first, use the linear combination shown in Figure 3.

- Set **Barrier** to 3 again, but this time increase **Tilt** to 1. How do the energy states change?
- Increase the tilt to 2. Do you see tunnelling now? If not, find a linear combination of eigenstates that gives rise to tunnelling. Set **Tilt** to 3 and repeat.

