Operations on a NV centre qubit

Previously, we have seen how we can control the electron spin of the NV center in diamond as a qubit. In this lecture, we will learn how we can use the NV center to also control multiple nuclear spin qubits, and how we can link NV centres together using photons to create a quantum network.

The first thing to realize is that this electron spin is surrounded by an entire cloud of nuclear spins. About 1% of diamond consists of Carbon-13, which is a spin-1/2 system and the rest consists of Carbon-12, which has no spin.

Now normally speaking, these nuclear spins are a source of decoherence. They flip-flop around randomly, and create a slowly-varying magnetic field on the NV-center. If we prepare the NV center in a quantum superposition state, then this fluctuating magnetic field changes the NV energy levels, that causes its phase evolution to become random and the quantum state is lost. This dephasing time is only about 5 microseconds, not that long.

Luckily, we can play a trick. We can apply a pulse that inverts the state of the NV. That if we flip it, this also inverts the effect of the magnetic field on the spin. So, if we have the same time before and after this flip, then the effect of the field exactly cancels and the quantum state is protected. We call this a spin echo. Of course this cancelation only works if the magnetic field is constant over time. But don't worry. As long as the field fluctuates slowly, we can just flip the electron spin multiple times, faster and faster, so that everything still averages out.

In this graph you can see that this works. We bring the electron spin in a super position and as we apply more and more pulses, we protect the electron spin longer and longer. In this way, we can even protect the quantum state for over a second, so really over macroscopic time scales and about six orders of magnitude better than without flipping the electron. We thus have very good coherence for the electron spins. How can we now use this to control multiple nuclear spins in the environment?

The key here is that if the electron spin is, let's say, in a state pointing downwards, then it creates a dipolar magnetic field. Each nuclear spin has a different position and angle from the electron spin, so that each of them feels a different magnetic field. This gives each nuclear spin a unique frequency, so that we can apply radiofrequency pulses that are resonant only with a particular targeted nuclear spin. We can selectively control the spins.

Moreover, if we now flip the electron to its zero state, it does not create a magnetic field. Now the same RF pulse will have no effect on this nuclear spin. The evolution of the nuclear spin thus depends on the state of the electron spin: it rotates if the electron spin is in state 1, but it doesn't rotate for state 0. This means we have a controlled quantum gate between the electron and nuclear spin. A CNOT. That is exactly what we need for quantum computation.

This enables us to control multiple nuclear spins near a single NV center. Each NV center becomes a system of 5 or even more qubits.

How do we link these NV centres together into a network? For that we use photons. Consider two NV centres in two different diamonds. We first make each of these NV centres emit a photon that is entangled with the spin state. And then we take these two photons and bring them together on a beam splitter. After this beam splitter it is fundamentally impossible to tell which photon came from which NV center. This means if the detectors behind the beam splitter register a certain pattern of photons, then we know, that for example, one of the NV centres is pointing up and the other one is pointing down. Because we fundamentally cannot know which one is up and which one is down, quantum mechanics tells us that we have created an entangled state between two distant NV centers. Note that this does not succeed every time you try. Not all measurement outcomes lead to entanglement and photons are also often lost on their way to the detectors. This is not a problem because we are just trying to create entanglement to use it as a resource to perform quantum computation in our network. So we can just keep trying and trying until we get the right measurement outcome, which then heralds the generation of entangled state, and then we can use it in the network.

This works. Here you see a state-of-the-art experiment in Delft, where we created entanglement between one NV center in the physics building, all the way on the left and another NV center, all the way on the right. About 1,3 kilometres away, at the other side of the Delft campus. This experiment was done to provide a more stringent test if quantum entanglement really exists. The outcome was yes, quantum mechanics is still correct. So, we can now go and use this entanglement to build quantum networks for quantum technology.

The next big step will be to combine the control of multiple qubits in each node with optical links to generate entanglement, in order to build increasingly larger quantum networks. Of course there are still many challenges. We need really good quantum control over all these spins and photons. We need to understand how to efficiently run quantum computations and error correction over these networks, and we need to build the complex electronics and software to control the networks. For this, we need physics, quantum computer science and engineering to come together. It will be really exciting to see if we can really build large-scale quantum networks and make quantum computation and quantum cryptography a reality.