NV center qubits

Today we are going to learn about a very promising type of quantum bit, spins associated to the nitrogen vacancy or NV center in diamond. This NV center consists of a substitutional nitrogen atom in the diamond lattice, next to a missing carbon atom, a vacancy. At this vacancy, some electrons are trapped, that form an electron spin that we can use as a quantum bit.

These NV centers have several unique features that make them promising for quantum information systems. First, the electron spin has a very long coherence time, even up to seconds; which means that we can control it as a good qubit. Quite remarkably, this qubit can even work in a large range of temperatures, all the way up to room temperature.

Second, this electron spin is not the only qubit we have in the system. It couples to nuclear spins in the environment, which gives us extra qubits to store and process quantum information. Additionally, the electron spin also interacts with photons, elementary particles of light. This makes it possible to send quantum states far away and to connect and entangle NV centers over a distance. With such a hybrid system of photons and spins we can create quantum networks.

In a quantum network we have nodes consisting of multiple spins or qubits that can store and process quantum states and we can then link these together using optics into a network. This is a very exciting approach. In this way we can make a large quantum computer by just connecting many copies of small and simple quantum processors together. This avoids the challenges of making a single chip of ever-increasing complexity. Because these optical connections can also go over long distances, we can use these networks for quantum cryptography as well which will enable fundamentally secure communication. Finally, one can even combine these two ideas and use the network to access a quantum computer remotely. In that way, even the party that hosts the quantum computer cannot know what computation you are performing or what the outcome is. How does such a computation work in a network?

The logical qubits, which actually hold the information of the computation, are spread out over the entire network. We use optical links to distribute quantum entanglement and we store and process that entanglement in the rest of the qubits. These entangled states are then used as a resource to perform error correction and the quantum computation, and these are also spread out over the entire network. What kind of samples do we use for this?

Here you see an image of a little diamond wired up in a chip in a cryostat, which we bring to 4 Kelvin. This is quite a bit a higher temperature than you will typically see for other qubits. If we zoom in, you see here a diamond which is just a few mm big. And if we zoom in even further with an electron microscope, we can see these structures. The grey background here is the surface of the diamond. The electrodes are used to apply electric fields to control the emission wavelength of the NV center, the colour it emits. And the microwave line is used to apply microwave fields that control the spin state. The half sphere is a lens that has been sculptured out of the diamond; we do this to get the photons effectively out of the diamond. Diamond has a very high refractive index. That is one of the reasons they are so shiny! But it also means that if we have flat surface we get a lot of total internal reflection. By curving the surface we can get about 10 to 20 times more light out.

In this fluorescence image you can see that we indeed have exactly one single NV center at the middle of the lens. The electronic spin of the NV is actually a spin 1. To use it as a qubit we just select two levels. We can control this spin by applying microwave pulses. If we start with the spin pointing upwards and we apply a microwave pulse of variable length, we can see that the spin rotates from up to down and then back up again in a coherent fashion. Exactly halfway in that rotation you have created quantum superposition of spin-up and down.

How can we measure what the state of the spin is? For that, we use optics. The idea is really quite simple. There are different optical transitions in the NV center, which are associated to different spin states. So, if we apply a laser pulse that is only resonant with a transition for spin up, then only when the spin is up we excite the NV center and we detect photons. If the spin is down, it stays dark. So in this way we can read out what the spin state is. This is not perfect, because the game is to catch at least one photon before the spin flips for some other reason. And that is why these solid immersion lenses on the sample that improve the light extraction are so important. Ok, that concludes the basic controls and measurement the electron spin of the NV center.

This is what it looks like in an actual laboratory. The tube that you see is a cryostat that contains the diamonds cooled down to 4 Kelvin. And you can also see a lot of optics and lasers to measure the spin and microwave electronics to control it. Of course in reality, when the system is running, it is dark, like this. That is because we have to detect single photons coming from the NV centers.

We will leave this running for now and in the next lecture, we will learn how we can control multiple qubits by using the NV center to control nuclear spins in the environment and also how we can use photons to link up NV centers into a quantum network. Thank you for joining us and have a great day!