Explained | What is Microsoft's planned 'quantum supercomputer'?

In a recent study, researchers reported that they had taken an important step towards topological quantum computing. What is it?

Updated – July 09, 2023 07:19 pm IST

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Representative image: U.S. President Joe Biden looks at the IBM System One quantum computer during a tour of an IBM facility in New York, October 6, 2022. | Photo Credit: AP

The story so far: In a paper published on June 21, researchers at Microsoft announced that they had figured out a way to create an elusive kind of particle that could potentially revolutionise quantum computing.

The claim pertains to particles called Majorana zero modes, whose unique properties could help build quantum computers that are much less fragile than they are today, making them computationally superior.

What does 'Majorana' mean?

All subatomic particles that make up matter are called fermions. (More accurately, only fermions can make up matter.)

In 1928, the British physicist Paul Dirac wanted to understand how quantum mechanics would change if it accommodated the special theory of relativity as well. The result was the Dirac equation, which described the behaviour of subatomic particles that moved at near the speed of light.

Dirac noticed that the equation predicted the existence of an antiparticle for each particle, such that if the two meet, they annihilate each other. Based on his prediction, scientists found the first antiparticle, the positron (or the anti-electron), in 1932. The discovery has been hailed as a good example of theory leading experiment.

A portrait of Ettore Majorana created in the 1930s. | Photo Credit: Public domain

In 1937, the Italian physicist Ettore Majorana found that the Dirac equation also allowed particles that satisfied certain conditions to be their own antiparticles. In his honour, fermions that are their own antiparticles are called Majorana fermions.

One subatomic particle that physicists think could be Majorana fermions are neutrinos. We don't yet have experimental proof that they are, however.

What is a Majorana zero mode?

All particles have four quantum numbers associated with them. No two particles in the same system can have the same four quantum numbers. The numbers are together like each particle's ID.

The characteristic feature of fermions is that one of these numbers, called the quantum spin, has only half-integer values, like 1/2, 3/2, 5/2, etc. This is why any particle, even something as large as an entire atom, can be a fermion: its total quantum spin needs to have a half-integer value.

This is also why two particles that are bound to each other in some way can be a fermion: again, their total quantum spin needs to have a half-integer value.

Most of the rules that apply to single fermions also apply to these pairs, or bound states.

When these bound states are their own antiparticles – i.e. if they meet, they annihilate each other – they are Majorana fermions. Physicists call such bound states *Majorana zero modes*, and have been looking for them for at least two decades.

How can Majorana zero modes help computing?

One reason they're of so much interest is that Majorana zero modes can be used to realise the more powerful topological quantum-computing. In fact, historically, the search for Majorana zero modes and advances in topological quantum-computing have often overlapped.

A quantum computer today can use individual electrons as qubits – its fundamental units of information. Information can be encoded in some property of each electron, like its spin. Then, the computer manipulates that information by having the electrons interact with each other according to the quirky rules of quantum mechanics.

These quirks are what make quantum computers better than classical computers: they allow the computers to access computational techniques and pathways not available to systems that are limited to the possibilities of classical physics.

For example, a qubit can have the values 0 and 1 at the same time thanks to a property called quantum superposition. But a semiconductor in a classical computer can have only one value at a time, 0 or 1.

On the flip side, quantum computers have a big problem: they're very fragile. Just tap your fingers on a table on which there's a computer and it could lose its quantummy abilities. That is, it could *decohere*.

An undated handout photo received on September 20, 2012 shows engineers making quantum devices at the Australian National Fabrication Facility at the University of New South Wales, Sydney. | Photo Credit: AFP

Now, say we have a Majorana zero mode that's an electron and a hole. A hole is a point where there could be an electron but isn't. It effectively has a positive charge. We can build a quantum computer whose qubit is such a Majorana zero mode. That is, we encode information onto some property of the mode.

The zero mode is composed of two entities (electron and hole), so say we pull the entities apart and keep them at a distance from each other. In this configuration, physicists have found that even if one of the entities is disturbed, the overall qubit doesn't decohere, and continues to protect the encoded information.

As one physicist told *Physics World* in 2021: "This concept is not so different from what Voldemort did in Harry Potter to protect his soul. He split into several horcruxes his Majorana zero modes."

In principle, if there is no overlap between the two 'half-particles', such a qubit can exist forever, Indian Institute of Science associate professor Anindya Das told this writer.

What does 'topological' mean?

The information is protected thanks to something called topological degeneracy.

Degeneracy in quantum mechanics means that the system has multiple states at the same energy. In topological systems, the system has multiple states at the lowest or ground state energy, i.e. the quantum system can exist in two (or more) possible states at its lowest energy. This is usually not possible: in its ground state – i.e. when the system has the least amount of energy – the system will have a particular configuration and will exist in a particular state.

If a system can exist in two possible states, or configurations, at its ground state, then the information encoded in that energy level can be recovered from one state or the other.

'Topological degeneracy' refers to a special case. Topology is the study of those properties of matter that don't change when it undergoes *continuous deformation* – i.e. when it's stretched, folded, twisted, etc., but not ruptured or glued to itself.

For example, a rubber band that's continuously deformed will continue to have one hole. A pair of shorts that's continuously deformed will always have three holes. This is why a rubber band (no matter how big) can't seamlessly transform into a pair of shorts. It will need to undergo a discontinuous deformation.

Put another way, the rubber band and the shorts are in topologically different states.

If they are also topologically degenerate, the rubber band and the shorts would be two possible states of the same system in its ground state. So the information can be stored between different topological properties, such as in the number of holes each state contains.

In effect, Majorana zero modes can work as qubits and they won't easily lose the information vested with them. This is why people building quantum computers are interested in finding them.

How else will topological quantum-computing be better?

A quantum computer based on Majorana zero modes could be interesting in other ways, too.

For example, it can take advantage of the peculiar mathematical rules that describe the behaviour of Majorana zero modes, called *non-Abelian statistics*. In these rules, changing the order of steps in which you perform a task changes the task's outcomes.

For example, say you have an algorithm that performs a series of steps in the order A-B-C-D. If the algorithm played according to the rules of non-Abelian statistics, A-C-B-D would give a different result from A-D-B-C.

So algorithms running on a quantum computer using Majorana zero modes will have one more degree of freedom than those running on a computer that doesn't.

Have Majorana zero modes been found?

The first big challenge today is to create Majorana zero modes in a system.

A popular example of a system that could give rise to them is a structure called a topological superconductor.

To be a Majorana zero mode, any bound state should satisfy two conditions: it should obey the Dirac equation and it should be its own antiparticle. A topological superconductor is built to allow particles to meet these conditions.

It consists of a semiconductor in the shape of a nanowire, with a superconducting sheath wrapped around it. The sheath covers a part of the nanowire. At one end, the nanowire is connected to a small junction through which electrons are fed into it A magnetic field is applied over the materials to complete the setup.

A schematic diagram of the experimental setup. (d) shows the arrangement of materials, including the semiconductor nanowire ("InAs") and the placement of the superconductor. | Photo Credit: Morteza Aghaee et al. (Microsoft Quantum), Phys. Rev. B 107, 245423

Here, Majorana zero modes are expected to exist at the ends of the nanowire, as a result of the interactions between the materials' electronic structures.

In a 2021 study, researchers created this setup but couldn't find Majorana zero modes. They were able to determine that the junction, where the electrons entered the nanowire, was the problem. Another paper, also published in 2021, claimed to have found Majorana zero modes, only for it to be retracted after some mistakes were found in its data.

These are just two examples from a plethora of studies. Scientists have also come up with many other ways to realise Majorana zero modes. But they are yet to be observed.

Apart from creating these 'particles', confirming that they are there is also tricky: they need to be inferred indirectly, from their effects on the surrounding material.

One way was thought to be the presence of a zero-bias conductance peak – the ability of an electric current to flow very easily in the absence of a voltage, while controlling some other parameters.

But studies later found that such a peak wouldn't be caused by Majorana zero modes alone, that they could be caused by other phenomena as well. This left the field in a mess, Dr. Das said.

What has the Microsoft team found?

In the new study, published on June 21, researchers from Microsoft reported engineering a topological superconductor made of an aluminium superconductor and an indium arsenide semiconductor.

They have said that this device was able to pass a "stringent protocol", based on measurements and simulations, that indicated with a "high probability" that it hosted Majorana zero modes.

The "stringent protocol" is called the topological gap protocol. According to the researchers, passing this protocol as well as observing the conductance peak is a smoking gun for Majorana zero modes.

According to Dr. Das, while topological quantum computing remains the ultimate goal, the existence of Majorana fermions hasn't been settled yet. The result will need to be independently confirmed.

Nonetheless, several news outlets reported that Microsoft had taken an important step towards a "quantum supercomputer".

For example, *TechCrunch* quoted Microsoft's VP of advanced quantum development saying "the company believes that it will take fewer than 10 years to build a quantum supercomputer using these qubits that will be able to perform a reliable one million quantum operations per second."

Dr. Das's estimate of the timeline for such a device was at least a century.

The paper itself concluded thus: "Continued improvement in simulation, growth, fabrication, and measurement capabilities will be required to achieve the topological gap required for ... coherent operations."

Published – July 09, 2023 10:30 am IST