Can you spot the quantum physics around your house?

Thinking of quantum physics in spooky ways overlooks its role in shaping the properties of the objects in our daily lives.

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Copper utensils hang on a string in a kitchen. | Photo Credit: Aurélien Lemasson–Théobald/Unsplash

“Sir, what is this Fermi energy? I can’t find a reasonable explanation. Which electrons have this energy and why?”

A visibly annoyed Hardik, one of my students, asked this as I started my class the other day. Hardik is one of a few undergraduate students taking a physics department elective course in IIT Kanpur, where I teach.

That copper, a garden-variety material that runs through the network of wires in our homes and lines the bottom of a few cooking utensils, has electrons at effectively at least 50,000° C was as surprising as it was worrisome for the students. And my insistent logic to prove this by assertion was not helping.

Forty-five degree celsius is already hot enough for the humans of Kanpur to curse at passersby. To imagine we are carrying “50,000-degree electrons” in our pockets should be difficult to contemplate. Water boils at 100° C; aluminium melts at 600° C, and 5,000° C is around the surface temperature of the sun. How then can we make sense of 50,000° C, that too inside everyday objects?

I could see why my students were upset.

What is quantum physics?

Quantum physics is often understood to be the physics of things that can both be 'located and absent' at a place, things that tunnel through walls, and things that can act across very large distances in an instant. But this is also a romantic conception that takes for granted, and thus overlooks, quantum physics's role in shaping the fascinating properties of the objects in our daily lives. Indeed, it offers a host of counterintuitive principles to grapple with, but it also makes some of the most quantitatively accurate predictions that we can actually test.

Take the Fermi energy of electrons in copper, for example. Quantum physics tells us that electrons are not particles like the little marbles that we play with. Instead, they are treated as waves, like the ones you see on a surface of water or that you create when you pluck a guitar string.

A wave is typically drawn like a curvy line (shaped like an 'S' but rotated 90°). Like all waves, an electron has a wavelength – the distance after which the wavy pattern repeats. The shorter an electron's wavelength, the more energy it holds. So a wave that changes smoothly has less energy than a wave that is more corrugated.

Consider this loose, and probably rather bad, analogy: you are driving a car over a series of speed bumps. If the bumps are smooth and vary slowly, you will have a lower energy. But if the bumps are sharp and modulate fast, you and your car will also oscillate faster and have more energy.

How does the wave nature matter?

Ripples on water. | Photo Credit: Jackson Hendry/Unsplash

One of the fundamental principles of this universe is that nature is lazy. More appropriately, everything tries to minimise the amount of energy it contains. A bunch of electrons in a metal would like to do the same thing as well, to lower their energy by being waves of larger and larger wavelengths. The largest wavelength they can take is however fixed – just about the size of the metal piece.

Now, it so happens that electrons are fermions, types of particles that are bound by Pauli's exclusion principle. The principle states that not all electrons in a system can have the same wavelength.

So now the electrons have a problem.

While they want to lower their energy, they can't all have the same longest possible wavelength. They need to have different wavelengths. As we increase the number of electrons in a material, every new electron we add has to have a shorter wavelength, and thus more energy. So the more electrons there are, the more energy every additional electron will have.

What's the highest such energy possible?

How many electrons does a simple block of metal, like a cupboard key, contain? In a metal such as copper, the copper atoms are about 10^{-10} m apart – that's ten-billionth of a metre, or one angstrom. The total human population is about 8 billion. Even if each copper atom has one electron, a cube of copper that is 1 cm to a side will have about a million billion billion electrons!

This in turn is a humongous number of electrons, which are all also behaving like waves that need to choose different wavelengths. And it turns out that the shortest wavelength they can reach is about one angstrom, about the distance between the copper atoms.

In this picture, we can estimate the energy of these highest-energy electrons: a couple of electron-volts (eV). eV is a unit of energy, just like temperature. If an object is at 27° C, we can also say that its temperature is about one-hundredth of an eV.

When electrons have such small wavelengths that they have high energies – a few eV – it translates to an effective temperature of tens of thousands of degrees celsius. This *highest energy* that the electrons are at is called the Fermi energy.

What does the Fermi energy mean physically?

Representative illustration. | Photo Credit: Jr Korpa/Unsplash

All metals around us have exorbitant Fermi energies. Copper has a Fermi energy of 80,000° C; aluminium, 130,000° C; and silver – the beautiful *chaandi* used in auspicious objects and jewellery – about 60,000° C. Note that this is an *effective* temperature, not the *actual* temperature. A metal is of course not this hot inside.

In fact, even if you take a block of metal to -273° C – the lowest temperature possible in the universe – the Fermi energy of its electrons will remain high.

The Fermi energy and the fermionic behaviour of electrons (i.e. due to the exclusion principle) follows from a basic quantum mechanical principle and is at the heart of all the properties of metals we see around us and take for granted. It's crucial to understand why metals reflect light (so we can see ourselves in a mirror), why they conduct electricity (so we have lights and fans), why they heat up easily (so they are good cooking utensils), and so on.

The next time you wonder whether you've encountered quantum physics, just like Hardik who was worried about the dizzying electrons, pick up a piece of metal around you – a key, a spoon, or a pen with a metal tip – and you'll be holding a beautiful quantum material in your hand.

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