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தினம் ஒரு குறள்

குறள் எண் **322**

கொல்லாமை

பகுத்துண்டு பல்லுயிர் ஓம்புதல் நூலோர்
தொகுத்தவற்றுள் எல்லாந் தலை.

இருப்பதைப் பகிர்ந்து உண்டு, பல உயிர்களையும் பாதுகாப்பது, நூல் எழுதியவர்கள் தொகுத்த அறங்களுள் எல்லாம் முதன்மையான அறமாகும். — சாலமன் பாப்பையா

How is the immune system kept in check?

What did the three Medicine Nobel awardees discover and why is it important? How do regulatory T cells function? How does their work on regulatory T cells lay the ground for a new field of research leading to new treatments for cancer and autoimmune diseases?

Ramya Kannan

The story so far:

The Nobel Prize season for 2025 began with the announcement of the Physiology or Medicine Prize on October 6. The three awardees – U.S.-based researchers, Mary E. Brunkow and Fred Ramsdell, and Japan's Shimon Sakaguchi – were chosen for their "discoveries concerning peripheral immune tolerance." Their discovery enabled a fundamental understanding of how the immune system works – how it is regulated and kept in check. This has led to the evolution of several new potential treatment options, currently being tested, including for cancer.

What does their discovery mean?

Unless the body's immune system is kept in check, it can attack its own organs. In that case, why do most people not develop autoimmune conditions where the body turns on itself? U.S. and Japanese scientists, working independently, arrived at an explanation for how the immune system is kept in check. It is for their work in making discoveries concerning what prevents the immune system from attacking the body that the Nobel was awarded. The laureates identified the immune system's regulatory T cells which perform the precise task of preventing immune cells from launching an attack on the body.

Literally every day the immune system, a formidable army, is on guard, battling pathogens that try to invade the body. The question here is how do these cells "know what they should attack and what they should defend", as the Nobel Committee pointed out. "Their discoveries have been decisive for our understanding of how the immune system functions and why we do not all develop serious autoimmune diseases," said Olle Kämpe, chair of the Nobel Committee.

Research is on to make sure that the immune system does not attack its own body

High honour: The Nobel Committee Secretary General after winners of the 2025 Nobel Prize in Medicine were announced in Sweden, on October 6. AFP

What are regulatory T cells?

The story goes back to Sakaguchi when he was working at the Aichi Cancer Centre Research Institute, Japan, some four decades ago. All T cells have special proteins called T-cell receptors on their surface. These receptors can be likened to a type of sensor. Using them, T cells can scan other cells to discover whether the body is under attack. There are a vast number of T cells with different receptors that can detect invaders, including new viruses. But they also have receptors that can attach to human tissues. But then, intuitively, is there a switch mechanism that warns the T cells off body cells?

In the 1980s, scientists realised that when T cells mature in the thymus, a small gland located in the upper chest behind the breastbone and in front of the heart that plays a crucial role in the immune system, they are taught to recognise and eliminate the body's own proteins in a process called central tolerance. By the time Sakaguchi began his research into trying to understand this mechanism, his colleagues had already reportedly performed an experiment on newborn mice. They hypothesised that the mice would develop fewer T cells and have a weaker immune system if they removed the thymus. Instead, the immune system went into overdrive and ran amok, with the little mice developing several autoimmune conditions. This experiment might not have satisfied its primary goal, but in it was the idea for a Nobel that would come about 30 years later. Sakaguchi took off from where the experiment stopped. He injected these mice with T cells and it appeared that the T cells could protect the mice from autoimmune diseases.

Veering off from the current scientific wisdom of the time, Sakaguchi was convinced that the immune system must have some form of security guard – one that calms down T cells and keeps them in check; in this case, protecting the mice from the autoimmune condition. It took him over a decade, but in 1995, he presented to the world, a new class of T cells to the world, those that carried an extra protein called CD25 on their surface. This was called the regulatory T cell. But other researchers were not convinced yet of this idea.

It would take a second act, and efforts from Brunkow and Ramsdell, to concretely prove the experiment. A new set of mice, being studied since the Manhattan Project in fact, stood up to the occasion. In this instance, half of all the male mice were sickly and died in a few weeks, while the females thrived. It turned out the male's organs were being attacked by T cells that destroyed the tissues. The Nobel-winning pair, who were then working at a biotech company Celltech Chiroscience in the U.S., realised that the mice could provide important clues in their work. After years of study, at an age when molecular biology was at best infantile, with a great deal of patience, they narrowed down on the faulty, mutant gene and named it Foxp3. They finally had an explanation for why a specific mouse strain was particularly vulnerable to autoimmune diseases. They also showed that mutations in the human equivalent of this gene cause a serious autoimmune disease, IPEX.

Two years later, Sakaguchi and others could prove, this time, convincingly, that the Foxp3 gene controls the development of the regulatory T cells, being able to prevent other T cells from mistakenly attacking the body's own tissue, in a process that is called peripheral immune tolerance. Regulatory T cells also ensure that the immune system calms down after it has attacked invaders, answering Sakaguchi's initial question.

What are the specific uses in medicine?

While specific therapies are yet to hit the market, over 200 studies involving regulatory T cells are currently in progress, said Thomas Perlmann, secretary-general of the Nobel Assembly, while making the announcement of the prize on October 6. These stand testimony to the potential slew of new treatment modalities to address various conditions.

This includes work on cancer – dismantling the regulatory T cells so that the immune system can access the tumours and set to work on them; and on autoimmune disorders where researchers are trying to promote the growth of more regulatory T cells, inside the body, but also outside of it, in order to make sure that the immune system does not attack its own body.

It is also believed that this research will have far-reaching implications for organ transplantation by regulating organ acceptance. Clinical studies are afoot to test many of these pathbreaking treatment modalities.

Topic:

Nobel Prize 2025 – Discovery of Regulatory T Cells and Peripheral Immune Tolerance

Source: The Hindu, 12th October 2025 (FAQ)

Relevance:

GS Paper 3 – Science and Technology (Biotechnology, Health and Immunology)
Also relevant for GS Paper 2 – Health Policy and Research

Linked Topics:

- Autoimmune Diseases
- Immunology and Human Health
- Biotechnology in Medicine
- Nobel Prizes and Scientific Contributions

Context:

- The 2025 Nobel Prize in Physiology or Medicine was awarded to **Mary E. Brunkow, Fred Ramsdell (U.S.)**, and **Shimon Sakaguchi (Japan)** for their **discoveries concerning peripheral immune tolerance**.
- Their research revealed how the immune system prevents attacking its own body — through **regulatory T cells (Tregs)** — a key mechanism that maintains immune balance and prevents autoimmune diseases.
- This discovery opened new frontiers in **cancer immunotherapy**, **autoimmune disorder treatment**, and **organ transplantation research**.

Curiosity Question:

If the immune system is designed to attack invaders, how does it avoid attacking the body's own healthy cells?

Analytical Overview:

The Discovery:

- In the 1980s, experiments showed that removing the **thymus** in newborn mice caused their immune system to attack their own organs — hinting that some "regulatory" mechanism was missing.
- **Shimon Sakaguchi (1995)** discovered a unique group of T cells with a surface protein **CD25**, later termed **Regulatory T Cells (Tregs)**.
- **Brunkow and Ramsdell** identified the **Foxp3 gene**, which controls the development of Tregs. Mutations in this gene lead to severe autoimmune diseases such as **IPEX syndrome**.

The Mechanism – Peripheral Immune Tolerance:

- The immune system "tolerates" the body's own tissues by distinguishing self from non-self.
- **Tregs** suppress immune responses when necessary, preventing overactivation.
- This process, known as **peripheral immune tolerance**, complements **central tolerance** (which occurs in the thymus).

Medical Implications:

- **Cancer Therapy:** Disabling Tregs can help the immune system attack tumours.
- **Autoimmune Diseases:** Boosting or transplanting Tregs can reduce immune attacks (e.g., in Type 1 diabetes, rheumatoid arthritis).
- **Organ Transplantation:** Manipulating Tregs may reduce organ rejection.
- Over **200 clinical trials** are underway exploring Treg-based therapies.

Scientific Significance:

- The discovery bridges **basic immunology and clinical medicine**.
- It demonstrates how **gene regulation (Foxp3)** can alter immune system behavior.
- It represents a paradigm shift in understanding **immune homeostasis** and **autoimmune pathology**.

Policy Linkages

Area	Key References
Health & Science Policy	National Health Policy 2017 – focus on biomedical innovation and translational research
Institutional Framework	ICMR, DBT, DST – support immunology and biotechnology research
Ethical/Legal Framework	National Guidelines for Stem Cell & Gene Therapy Research (ICMR)
International Cooperation	India's participation in global biomedical research initiatives (WHO, UNESCO)

Recommendations:

- **Boost Immunology Research Capacity:** Strengthen research infrastructure in immunology, molecular biology, and biomedical engineering.
- **Translational Medicine Focus:** Encourage public–private partnerships to convert lab discoveries into therapies.
- **Ethical Regulation:** Create robust ethical oversight for gene editing and immune-modulation studies.
- **Skill and Education:** Introduce advanced immunology modules in medical and biotechnology curricula.
- **International Collaboration:** Collaborate globally for trials, patents, and shared databases on autoimmune and cancer research.

Prelims Pointers:

- **T Cell:** A type of white blood cell (lymphocyte) that plays a central role in the adaptive immune response.
- **Regulatory T Cells (Tregs):** Subset of T cells that suppress overactive immune responses and maintain immune tolerance.
- **Foxp3 Gene:** Controls Treg cell development; mutations cause autoimmune disorders like IPEX.
- **Peripheral Immune Tolerance:** Mechanism that prevents immune cells from attacking body tissues.
- **Thymus Gland:** Site of T-cell maturation and central tolerance.
- **CD25 Protein:** Surface marker identifying regulatory T cells.

Mains Keywords:

- Peripheral Immune Tolerance
- Regulatory T Cells (Tregs)
- Foxp3 Gene
- Autoimmune Diseases
- Cancer Immunotherapy
- Translational Medicine
- Biomedical Innovation

Mains Practice Question: "The discovery of regulatory T cells has redefined our understanding of immune tolerance and autoimmune diseases." Discuss its scientific and medical significance.

Dimensions:

- **Scientific Dimension:** Role of Tregs, Foxp3 gene, immune regulation mechanism.
- **Medical Dimension:** Applications in cancer, autoimmunity, and organ transplantation.
- **Ethical/Policy Dimension:** Biomedical research governance, ethics of immune manipulation.

One-Line Takeaway:

The 2025 Nobel-winning discovery of regulatory T cells marks a breakthrough in understanding immune tolerance, unlocking future therapies for cancer, autoimmune diseases, and transplant medicine.

UPSC PYQ Linkage:

- **UPSC GS Paper 3 (2019):** “What do you understand by genome editing? Discuss the ethical concerns associated with it.”
- **UPSC GS Paper 3 (2021):** “How is CRISPR technology transforming medical research?”
- **UPSC GS Paper 2 (2020):** “Discuss India’s potential in biomedical research and innovation.”

Why did MOFs pioneers win the chemistry Nobel?

How are metal-organic frameworks being put to use across different applications? Why are they significant?

Vasudevan Mukunth

The story so far:

For centuries, chemistry's main terrain was to craft ever more complex molecules but it soon became clear to scientists that they were all confined to their own boundaries. The Nobel Prize in Chemistry 2025 honours three scientists who expanded that horizon. Susumu Kitagawa, Richard Robson, and Omar Yaghi have been feted for developing metal-organic frameworks (MOFs), little molecular scaffolds with vast internal spaces where other atoms and molecules can move, react or stay.

What is an MOF?

MOFs are crystalline structures in which metal ions serve as nodes and organic molecules as connectors. The resulting structure can have enormous internal surface areas – thousands of square metres per gram – and their pores can be customised to attract or hold specific molecules. By carefully choosing the building blocks, researchers can control the size and shape of the cavities and the chemical environment within. MOFs are thus among the most versatile materials ever created.

What did Robson and Kitagawa achieve?

In the 1970s, Richard Robson at the University of Melbourne was preparing ball-and-stick models to show students how atoms connect. He realised that the positions of the holes drilled into each atom contained all the information needed to determine the molecule's shape. If that logic worked for small molecules, he wondered if it could be scaled up.

An MOF called CALF-20 can efficiently capture carbon dioxide from factory exhaust and is already being tested in industrial plants

A decade later, Robson combined copper ions, which like to bond in a tetrahedral arrangement, with an organic molecule bearing four arms ending in nitrile groups. To everyone's surprise, instead of a messy tangle, the components self-assembled into a diamond-like crystal. This lattice wasn't dense like a diamond but full of empty cavities, each capable of hosting other molecules. Robson predicted that such "frameworks" could be tailored to trap ions, catalyse reactions, and sieve molecules by size.

However, Robson's early crystals were fragile. Susumu Kitagawa in Japan made them stable and functional. Guided by his philosophy of finding "usefulness in the useless", Kitagawa pursued porous materials even when they seemed too delicate to matter. In 1997, he used cobalt, nickel or zinc ions linked by a bridging molecule called 4,4′-bipyridine to build a true three-dimensional MOF. When the material was dried and refilled, gases such as methane, nitrogen, and oxygen could flow in and out without damaging the structure.

Kitagawa also recognised that MOFs could be soft rather than rigid, with flexible molecular joints allowing them to expand, contract or bend around depending on temperature, pressure, and the molecules inside.

What was Yaghi's contribution?

Omar Yaghi in the U.S. gave MOFs their structural strength and reproducibility. Having grown up in modest circumstances in Jordan, Yaghi was fascinated by chemistry's ability to create new forms of order. At Arizona State University in the 1990s, he sought a way to build extended materials by design, not by chance, using metal ions as joints and organic molecules as struts. In 1995, he made the first two-dimensional frameworks linked by cobalt or copper ions that could host other molecules without collapsing. Four years later, he achieved a landmark with MOF-5, a robust three-dimensional lattice made from zinc ions and benzene-dicarboxylate linkers. MOF-5 was strong and, notably, just a few grams had an internal surface area comparable to a football field. It was also intact when heated to 300°C and emptied of all 'guest' molecules.

By the early 2000s, his team had built entire families of MOFs with the same underlying geometry but different pore sizes and functions.

Why are MOFs important?

Chemists can easily make use of them for different applications. An MOF called CALF-20 can efficiently capture carbon dioxide from factory exhaust and is already being tested in industrial plants. MOF-303 can harvest drinking water from arid desert air by absorbing vapour at night and releasing it in sunlight. UiO-67 can remove persistent forever chemicals (PFAS) from water. MIL-101 and ZIF-8 can speed up the breakdown of pollutants and recover rare-earth metals from wastewater.

In the energy sector, NU-1501 and MOF-177 can store hydrogen or methane safely at moderate pressure, a crucial step toward clean-fuel vehicles. Others serve as containers for toxic gases in semiconductor manufacturing and as drug-delivery capsules that release medicines in response to biological cues.

Topic:

Nobel Prize 2025 – Discovery and Development of Metal-Organic Frameworks (MOFs)

Source: The Hindu, 12th October 2025 (FAQ)

Relevance:

GS Paper 3 – Science and Technology (Nanotechnology, Material Science, Energy & Environment Applications)

Also relevant for GS Paper 2 – Environmental Governance & Sustainable Technology

Linked Topics:

- Carbon Capture and Climate Technology
- Hydrogen Economy and Clean Fuels
- Water Harvesting & Environmental Sustainability
- Nanomaterials and Advanced Chemistry

Context:

- The **2025 Nobel Prize in Chemistry** was awarded to **Susumu Kitagawa (Japan)**, **Richard Robson (Australia)**, and **Omar Yaghi (U.S.)** for their pioneering work in developing **Metal-Organic Frameworks (MOFs)** — crystalline materials made of metal ions and organic linkers.
- MOFs are revolutionizing modern chemistry by offering **ultra-high porosity**, **customizable molecular cavities**, and **applications in energy storage, carbon capture, and clean technologies.**

Curiosity Question:

How can a few grams of a material have a surface area equal to an entire football field — and why does that matter for solving real-world problems like pollution and energy storage?

Analytical Overview:

What are MOFs?

- **Metal-Organic Frameworks (MOFs)** are **crystalline structures** made from **metal ions (nodes)** and **organic molecules (linkers)**.
- They have **enormous internal surface areas (up to thousands of m² per gram)** and **tunable pores** that can selectively capture, store, or filter molecules.
- Function like "molecular sponges" or "lego-like frameworks" for specific applications.

Pioneering Contributions:

- **Richard Robson (1970s–80s):** Discovered that metal ions and organic molecules could self-assemble into **porous, diamond-like frameworks** — predicting their use in trapping and catalysis.
- **Susumu Kitagawa (1990s):** Built **stable 3D MOFs** using cobalt, nickel, and zinc; developed **"soft MOFs"** with flexible molecular joints, enabling reversible gas absorption.
- **Omar Yaghi (1995–2000):** Created the **first robust and reproducible MOFs** (notably **MOF-5**), introducing **rational design principles** to construct materials with predictable geometry and high thermal stability.

Applications and Impact:

- **Climate & Environment:**
    - **CALF-20:** Captures CO_2 from industrial exhaust.
    - **MOF-303:** Harvests water from desert air.
    - **UiO-67:** Removes PFAS ("forever chemicals") from water.
    - **MIL-101, ZIF-8:** Break down pollutants, recover rare-earth metals.
- **Energy Sector:**
    - **NU-1501, MOF-177:** Store hydrogen and methane safely for clean-fuel technologies.

- **Healthcare:**
    - Used as **drug-delivery carriers** and **toxic gas absorbers**.
- **Industrial Applications:**
    - Catalysis, separation, and semiconductor manufacturing safety.

Why It Matters:

- MOFs bridge chemistry, nanotechnology, and sustainability.
- Their modular design allows **atomic-level control of material properties.**
- They contribute to **SDG 7 (Affordable & Clean Energy)** and **SDG 13 (Climate Action).**

Policy Linkages

Area	Key References
Science & Tech Policy	Science, Technology & Innovation Policy (STIP) 2020; National Hydrogen Mission; National Mission on Materials Research
Environmental Linkage	National Carbon Capture and Utilisation Policy (draft); Paris Agreement commitments
Institutional Support	CSIR, DST, and IISc-led research on nanomaterials and MOFs
SDG Goals	SDG 7 – Clean Energy; SDG 9 – Industry, Innovation, Infrastructure; SDG 13 – Climate Action

Recommendations:

- **Promote Indigenous Research:** Encourage India-led R&D in MOF synthesis for carbon capture, hydrogen storage, and desalination.
- **Industry-Research Collaboration:** Link chemical industries and research institutions for technology translation.
- **Sustainable Deployment:** Ensure MOF production and disposal remain eco-friendly and scalable.
- **Skill Development:** Train scientists in **advanced materials chemistry** and **molecular design**.
- **Integration with National Missions:** Align MOF-based innovations with the **National Hydrogen Mission**, **Atmanirbhar Clean Tech**, and **Make in India** initiatives.

Prelims Pointers:

- **Metal-Organic Frameworks (MOFs):** Crystalline materials made of metal ions (nodes) and organic linkers forming porous 3D structures.
- **MOF-5:** First robust 3D MOF developed by Omar Yaghi; made of zinc and benzene-dicarboxylate linkers.
- **CALF-20 / MOF-303:** Examples of MOFs used for CO_2 capture and water harvesting.
- **ZIF-8, MIL-101:** MOFs used for pollutant breakdown and metal recovery.
- **Surface Area:** MOFs can have internal surfaces exceeding **1,000 m² per gram**.
- **Porosity:** Pore size and shape can be customized chemically.

Mains Keywords:

- Metal-Organic Frameworks (MOFs)
- Porous Materials
- Carbon Capture
- Hydrogen Storage

- Green Chemistry
- Nanomaterials
- Sustainable Energy Technologies

Mains Practice Question:

"Metal-Organic Frameworks represent a paradigm shift in material chemistry, bridging environmental sustainability and nanotechnology." Discuss.

Dimensions:

- **Scientific Dimension:** Structure, properties, and design of MOFs.
- **Environmental Dimension:** Role in carbon capture, pollution control, and water purification.
- **Energy Dimension:** Hydrogen/methane storage and clean energy applications.
- **Industrial Dimension:** Catalysis, separation, and large-scale feasibility.

One-Line Takeaway:

The 2025 Nobel Prize in Chemistry celebrates the creation of Metal-Organic Frameworks — molecular scaffolds with vast inner spaces that promise cleaner air, renewable fuels, and sustainable materials for the future.

UPSC PYQ 2022

Consider the following statements:

1. **Other than those made by humans, nanoparticles do not exist in nature.**
2. **Nanoparticles of some metallic oxides are used in the manufacture of some cosmetics.**
3. **Nanoparticles of some commercial products which enter the environment are unsafe for humans.**

Which of the statements given above is/are correct?

a) 1 only

b) 3 only

a) 1 and 2 only

b) 2 and 3 only

Answer: (d)

What is macroscopic quantum tunnelling?

What did the three physics Nobel laureates conduct research on? How will their findings open the door to emerging technologies used to collect information? What can a circuit with a Josephson junction mimic? How will it help superconducting quantum processors?

Vasudevan Mukunth

The story so far:

Particles can sometimes cross barriers they don't have the energy to climb, like boring through a mountain instead of scaling it first, as per quantum mechanics. This process, called tunnelling, is common in nuclear and atomic physics. The 2025 physics Nobel Prize laureates John Clarke, Michel Devoret, and John Martinis showed that such behaviour can occur not only in subatomic particles but also in an electrical circuit made of superconductors.

The laureates' experiments provided a template to make reliable quantum measurements in solid-state devices

What is a Josephson junction?

The fundamental unit of the award-winning experiments the trio conducted is a device called a Josephson junction. Here, two superconductors are separated by a very thin insulator. The trio wanted to know if a parameter of the circuit as a whole, in this case the junction's phase difference, could behave like a single quantum particle. They came away from their experiments with a resounding 'yes', by observing both macroscopic quantum mechanical tunnelling and discrete energy levels in the circuit. In a superconductor, many electrons pair up and move without resistance. In a Josephson junction, the phase difference between the two superconductors measures how out of step the collective quantum wave of paired electrons is on one side compared with the other. This phase's value controls how easily the pairs can cross the insulating barrier. When this phase becomes trapped in an 'energy valley', quantum mechanics allows it to tunnel through to the other side, producing a small but measurable voltage across the junction.

When the scientists sent a current through the Josephson junction, they found that if it was small enough, the flow of paired electrons was stalled by the insulator and the circuit produced no voltage. In classical physics, this state would never change: the electrons' flow would remain blocked. But in the quantum world, the current has a small chance of suddenly tunnelling through the insulator and flowing freely on the other side, creating that voltage.

In awe: Awardees of the 2025 Nobel Prize in Physics are seen on screen at the Royal Swedish Academy of Sciences in Stockholm, Sweden, on October 7. AFP

Why was the circuit fragile?

In the early 1980s, several groups searched for this tunnelling by varying the current and recording the value at which the junction produced a voltage. If the electron pairs were simply escaping to the other side due to thermal fluctuations – akin to being heated enough to jump across the mountain – cooling the device ought to steadily increase the amount of current required to produce a voltage. On the other hand, if the electron pairs were tunnelling through, the rate of crossing over would eventually stop changing with temperature. Simple though the setup was, the challenge was in keeping stray microwave radiation from affecting the circuit and producing data consistent with the temperature-independent behaviour. So the experimenters needed to reduce and characterise environmental noise with great care.

The team led by Clarke, working with Devoret and Martinis, solved this problem by redesigning their setup so stray signals couldn't interfere. They used special filters and shielding to block unwanted microwaves and kept every part of the experiment extremely cold and stable. Then they sent in faint yet precisely tuned microwave pulses to gently test how the circuit responded, allowing them to measure its electrical properties accurately. When they finally cooled the system to very low temperatures, they saw that its behaviour matched the exact patterns predicted by quantum tunnelling theory.

How did the circuit show quantum effects?

The researchers also wanted to find out if the circuit's trapped state behaved like a quantum system with distinct energy steps – a hallmark of a quantum state – instead of a smooth range. They shone microwaves of different frequencies onto the junction while adjusting the current. When the frequency exactly matched the gap between two allowed energy levels, the circuit suddenly escaped more easily from its trapped state. The higher the level, the faster this escape happened. These patterns showed that the circuit's overall state could only receive or emit fixed packets of energy, which is also how a single particle following the rules of quantum mechanics would behave. In short, the circuit as a whole behaved like a quantum particle.

Put together, the results revealed two facts. First, a macroscopic electrical circuit – one that you could see with the naked eye – could display quantum behaviour when sufficiently isolated from its environment. Second, a relevant macroscopic variable in that circuit could be understood using the standard tools of quantum mechanics. These experiments also pointed to a practical path for controlling and 'reading' macroscopic quantum states – in this case using a bias current, weak microwaves, and sufficient protections to shield from external radiation – one that gave the field a template to make reliable quantum measurements in solid-state devices. Subsequent work extended these ideas, developing superconducting qubits, embedding them in microwave resonators, and improving their coherence.

What are the applications of this work?

The technological applications flow from the same physics. A circuit with a Josephson junction can be made to mimic the quantised energy levels of an atom; microwaves could drive the circuit to jump between these energy levels; and carefully coupling the circuit to a resonator could allow an operator to measure changes in the circuit without disturbing it. This architecture, known as circuit quantum electrodynamics, is the foundation of many of today's superconducting quantum processors (The resonator is like an echo chamber for microwaves. When the circuit is coupled to a resonator, the two can exchange energy in a controlled way, allowing scientists to measure the circuit's state indirectly by observing changes in the resonator's behaviour).

Superconducting circuits that exploit macroscopic quantum effects are central to several emerging technologies. They are quantum amplifiers that boost extremely weak signals without adding noise – a useful ability in diagnostics as much as searches for dark matter. They are used to measure current and voltage with extraordinary precision. They can be microwave-to-optical converters that link quantum processors to fibre-optic networks. They are components in quantum simulators used to model complex materials or even chemical reactions atom by atom.

Topic: 2025 Nobel Prize in Physics – Macroscopic Quantum Tunnelling

Source: The Hindu (12th Oct 2025) – (FAQ)

Relevance: GS Paoer 3 - Science & Technology | Quantum Mechanics | Nobel Laureates 2025

Linked Topics:

- Superconductivity
- Quantum Tunnelling
- Josephson Junction
- Quantum Computing
- Circuit QED

Context:

The 2025 Nobel Prize in Physics has been awarded to **John Clarke, Michel Devoret, and John Martinis** for demonstrating **quantum tunnelling and discrete energy states** in macroscopic superconducting circuits — bridging quantum physics and electrical engineering.

Curiosity Question:

How can an **electrical circuit visible to the naked eye** behave like a **quantum particle**?

Analytical Overview:

Quantum Tunnelling Concept:

- In quantum mechanics, particles can “tunnel” through barriers they lack the energy to overcome — an effect impossible in classical physics.
- Common in nuclear decay and atomic physics.

Josephson Junction — The Core Device:

- Comprises **two superconductors** separated by a **thin insulating barrier**.

- The **phase difference** between superconductors governs the tunnelling of paired electrons (Cooper pairs).
- When trapped in an energy valley, the phase can "tunnel" through the barrier, generating a measurable voltage.

The Breakthrough:

- The trio showed that this **phase variable behaves as a single quantum entity**.
- Observed **quantum tunnelling** and **discrete energy levels** in a macroscopic circuit.
- Achieved by **shielding against external radiation** and **cooling to ultra-low temperatures**.

Significance of the Findings:

- Proved that **macroscopic systems can display quantum behaviour**.
- Provided a **framework for quantum control and measurement** in solid-state systems.
- Paved the way for **superconducting qubits** — the foundation of quantum computing.

Policy Linkages:

- **National Quantum Mission (India, 2023–2031):** Supports quantum computing, communication, and sensing research.
- **Science, Technology, and Innovation Policy (STIP 2020 Draft):** Encourages indigenous R&D in quantum and superconducting technologies.

Recommendations:

- Strengthen **India's Quantum Mission** by enhancing cryogenic infrastructure and global research collaborations.
- Promote **quantum hardware innovation** through academia–industry partnerships.

- Encourage indigenous production of **superconducting materials** and precision electronics.

Prelims Pointers:

- **Josephson Junction:** Two superconductors separated by a thin insulator; allows tunnelling of Cooper pairs.
- **Quantum Tunnelling:** Particle crosses a potential barrier without enough classical energy.
- **Superconductivity:** Zero electrical resistance and expulsion of magnetic field below critical temperature.
- **Circuit QED:** Interaction of superconducting circuits with microwave resonators.
- **Applications:** Quantum computing, quantum amplifiers, dark matter detection, quantum communication.
- **Cryogenics:** Ultra-low temperature systems used to study superconductivity.

Mains Keywords:

Quantum Tunnelling | Superconductivity | Josephson Junction | Macroscopic Quantum Behaviour | Quantum Circuits | Quantum Computing | Cryogenics | Circuit QED

Mains Practice Question (with Dimensions):

The 2025 Nobel Prize in Physics highlighted the quantum nature of macroscopic systems. Discuss the scientific significance and technological implications of this discovery in the context of India's Quantum Mission.

Dimensions:

- Quantum tunnelling & Josephson junction mechanism
- Experimental validation and macroscopic quantum behaviour
- Role in quantum computing and circuit QED
- India's roadmap under National Quantum Mission

One Line Takeaway:

The 2025 Nobel Physics Prize proved that **macroscopic superconducting circuits can behave like quantum particles**, laying the foundation for today's **superconducting quantum computers**.

UPSC PYQ

Which one of the following is the context in which the term "qubit" is mentioned?

(a) Cloud Services

(b) Quantum Computing

(c) Visible Light Communication Technologies

(d) Wireless Communication Technologies

Ans: (b)

Mains 2020

"The emergence of the Fourth Industrial Revolution (Digital Revolution) has initiated e-Governance as an integral part of government". Discuss. **(2020)**