QUANTUM NOISE – SCIENCE AND TECHNOLOGY

NEWS: Recently, new research by **Raman Research Institute** reveals that **quantum noise**, once seen as a threat to quantum systems, can **preserve or even generate intraparticle entanglement**, challenging traditional views on **decoherence and quantum stability**.

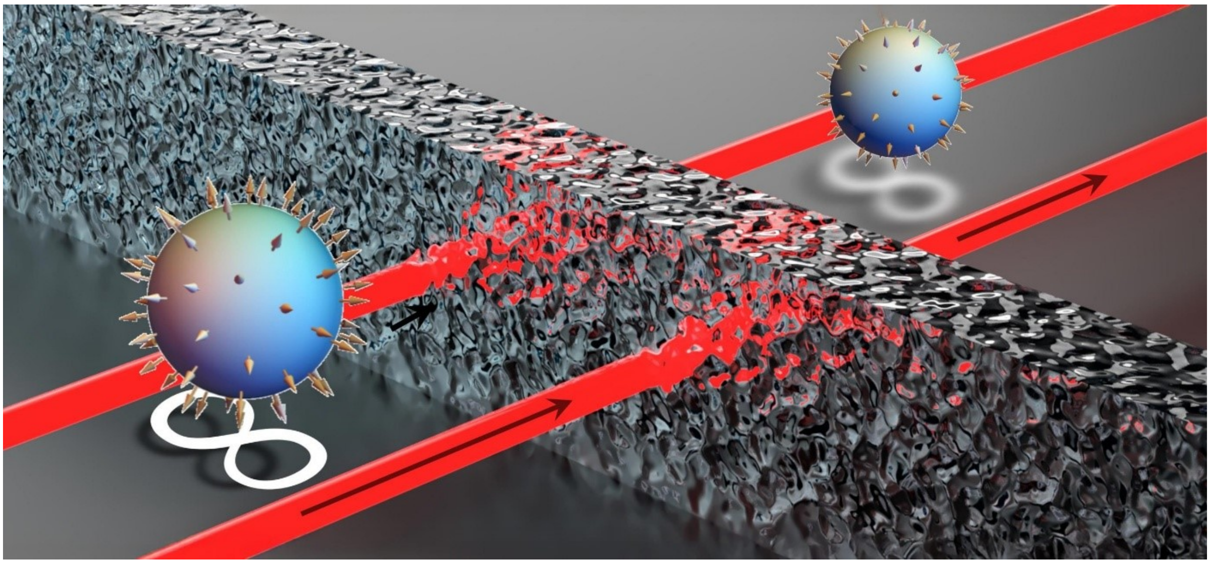
WHAT'S IN THE NEWS?

What is Quantum Noise?

- **Definition and Nature**:
  Quantum noise refers to the **unavoidable, intrinsic fluctuations in a quantum system**, arising due to the **fundamental limits of measurement and disturbance** described by the **Heisenberg Uncertainty Principle**.
  These fluctuations are not due to experimental error but are **inherent to quantum mechanics itself**.
- **Heisenberg Uncertainty Principle (1927)**:
  Proposed by **Werner Heisenberg**, the principle states that **one cannot simultaneously know both the exact position and exact momentum of a quantum particle** (like an electron or photon).
  This uncertainty introduces natural fluctuations, giving rise to **quantum noise** in any measurement or control of quantum systems.

Sources of Quantum Noise

- **Intrinsic (Fundamental) Sources**:
  - **Vacuum Fluctuations**: Even in "empty space," quantum fields exhibit **random energy variations** due to the uncertainty principle.
  - **Shot Noise**: Arises from the **discrete, probabilistic nature** of quantum particles arriving at detectors, particularly relevant in photonics and quantum optics.
- **Extrinsic (Environmental/Instrumental) Sources**:
  - **Thermal Fluctuations**: Caused by ambient temperature, leading to decoherence in quantum states.
  - **Electromagnetic Interference**: External fields can disturb quantum coherence.
  - **Mechanical Vibrations and Crosstalk**: Affect sensitive quantum devices, especially in trapped ion and superconducting qubit platforms.
  - **Gate and Instrument Imperfections**: Errors in quantum logic operations (gates) introduce noise that alters system dynamics.



Types of Quantum Noise Studied in Quantum Systems

- **Amplitude Damping Noise**:
  - Models **energy loss**, where a quantum system (like an excited atom or photon) **spontaneously decays to a lower energy state**, emitting energy into the environment.
- **Phase Damping (Dephasing)**:
  - Affects the **relative phase between quantum states** without energy loss, disrupting **quantum interference** and **superposition** properties.
- **Depolarizing Noise**:
  - Introduces **random errors in all directions**, effectively turning a pure quantum state into a **completely mixed state**, destroying both **superposition and entanglement**.

Quantum Entanglement – Basic Concepts

- **Definition**:
  A uniquely quantum phenomenon where **two or more particles become correlated** such that the **quantum state of one cannot be described independently** of the other, even across large distances.
- **How it Works**:
  - A **light source emits two entangled photons**.
  - Although each photon's polarization is random, the **measurement outcomes are always correlated**—if one is vertical, the other is too, and vice versa.
  - This non-local correlation defies classical physics and is described as "**spooky action at a distance**" by Einstein.
- **Example Using Beam Splitter**:
  - A single photon enters a 50–50 beam splitter.

- It enters a **superposition** of being in **Path A and Path B simultaneously**.
- Measuring one path **instantly affects the probability of the other path**, showcasing entanglement.

Types of Entanglement Affected by Quantum Noise

- **Intraparticle Entanglement**:
    - Entanglement **within a single particle**, such as between **spin and polarization degrees of freedom** in a single photon.
    - **Key Discovery**: This type of entanglement can **survive, revive, or even be generated under certain noise conditions**, making it **more robust and resilient**.
- **Interparticle Entanglement**:
    - Involves **two or more distinct particles**.
    - **Key Finding**: This form of entanglement tends to **degrade irreversibly under the same quantum noise**, suggesting it is **more fragile** in noisy environments.

Significance of These Discoveries

- **Paradigm Shift in Understanding Noise**:
    - Traditionally, noise is seen as detrimental in quantum systems.
    - However, the **research reveals that noise can, under the right conditions, help generate or preserve certain forms of entanglement**, especially **intraparticle entanglement**.
- **Improved Decoherence Resistance**:
    - **Intraparticle entanglement's ability to endure noise** offers potential for **more stable quantum computing, communication, and sensing systems**, particularly in real-world, noisy environments.
- **New Frameworks for Quantum Technology Design**:
    - Encourages the **development of noise-resistant quantum protocols** and architectures that **leverage instead of eliminate quantum noise**, especially for **quantum cryptography, quantum teleportation**, and **quantum error correction**.
- **Cross-Platform Validity**:
    - The results are **independent of hardware type**, applicable to **photons, neutrons, trapped ions, and more**, thanks to the **global noise model** that treats the quantum system holistically.

Source: https://www.pib.gov.in/PressReleasePage.aspx?PRID=2144514