DEPARTMENT OF PHYSICS

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The quantum traffic jam

By ANKUR MAJUMDER

Some materials conduct electricity, and some do not — simple, right? In the quantum world, though, "simple" often turns into surprising. Imagine a six-lane highway with plenty of empty space, and yet traffic is locked in a complete standstill with no accident or roadwork in sight. That is the quantum oddity condensed-matter physicists call a Mott insulator: a system that should behave like a metal but instead refuses to let electrons flow. The reason is not a lack of available states, but the electrons themselves — they repel each other so strongly that they lock into place.

Awards and Recognitions

Prof. Ram Bilash Choudhary received the Jharkhand Best Teacher Award, **Prof. Bobby Antony** received the Fellowship of the Institute of Physics (FInstP), and **Dr. Sk. Riyajuddin** became an Editorial Board Member of Nature Scientific Reports.
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Before we dive into the mystery, let us establish the familiar baseline. In an ordinary insulator—like the rubber coating on a wire—electrons are tightly bound to their atoms. Imagine a parking lot so full that there is literally no space for any car to move. That is your conventional insulator: no empty spaces mean no electron motion, hence no electrical conductivity. The physics here is straightforward and elegant. However, nature throws us a curveball — Mott insulator. In a Mott insulating state, the parking lot is half empty. There are plenty of empty parking spaces available. According to conventional wisdom, those electrons should be zipping around freely, making the material an excellent conductor. Yet paradoxically, they refuse. They absolutely will not move. The reason? The electrons despise each other. The electrostatic repulsion between neighbouring electrons is so powerful that it creates a self-imposed barrier —a collectively ordained traffic jam that emerges purely from their mutual animosity. This strange phenomenon vexed physicists for decades. In 1949, Sir Nevill F. Mott argued (mid-20th century) that strong Coulomb repulsion could localize electrons even where band theory predicted metallic behaviour — hence the name “Mott insulator." For his fundamental contributions to the understanding of the electronic structure of magnetic and disordered systems, Mott shared the 1977 Nobel Prize in Physics—a recognition of the transformative impact of this conceptual shift. Soon after, John Hubbard introduced a minimal lattice model (the Hubbard model) that captures the essential competition: kinetic energy that delocalizes electrons versus on-site Coulomb repulsion that localizes them. P. W. Anderson later emphasized how disorder and correlations can conspire in surprising ways. These conceptual advances laid the groundwork for a rich field that combines many-body theory, numerical methods, and experiments. Can we actually predict where this transition occurs? Actually, solving interacting quantum systems exactly is notoriously difficult. In fact, the Hubbard model is solved exactly only for the one-dimensional case using a sophisticated analytical technique (via Bethe ansatz). You can always argue that if this problem cannot be solved only using pen and paper, why not take the help of computers? Let us suppose you try to solve this problem by brute-force diagonalization of the many-body Hamiltonian matrix. In that case, you will soon realize that solving for a few sites, say more than 100, will require a hard drive bigger than the Milky Way galaxy; therefore, studying real systems at the thermodynamic limit (Avagadro’s number of lattice sites) is out of question. So, what is the way out? This is where one of the most powerful techniques in modern theoretical physics comes into play: Dynamical Mean Field Theory (DMFT). Originally developed in the late 1980s and early 1990s by researchers including Antoine Georges, Gabriel Kotliar, Walter Metzner, and Dieter Vollhardt, DMFT represents a conceptual breakthrough in how we approach strongly correlated systems. Rather than trying to solve for the entire quantum system at once—an impossible task for any realistic material—DMFT employs an elegant mathematical trick. Imagine focusing on a single electron in your material, surrounded by all the others. That electron experiences an average, effective "field" created by all its neighbors. If you can calculate how this single electron behaves in this average field, you’ve captured the essential physics. The brilliance of DMFT is that it becomes exact in the limit of high dimensionality, and it provides surprisingly accurate results even in lower dimensions where materials actually exist. Now, why is it called "dynamical" mean field theory, and what advantage does this provide?

The key lies in understanding quantum temporal fluctuations. Unlike classical mean-field approaches—such as the classical Ising model with its static, time-independent mean field—DMFT is inherently dynamic.

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It incorporates the quantum fluctuations that occur in time as electrons interact with their environment. Instead of treating the effective field as a mere number, DMFT treats it as a time-dependent quantity, capturing how an electron's experience changes moment by moment as it exchanges energy and quantum information with its surroundings. This temporal dimension is crucial, as it enables DMFT to capture the rich dynamics of quantum phase transitions, the emergence of quasiparticles, and the fine structure of spectral features that classical mean-field theories miss entirely. In essence, DMFT recognizes that quantum mechanics is fundamentally about temporal evolution, and any theory worthy of capturing its essence must respect this temporal nature. However, DMFT has a complementary limitation: because it solves a single-site problem embedded in an effective bath, it cannot capture spatial correlations between distant sites. The assumption of a local, uniform mean field breaks down when correlations are inherently non-local or when the system has spatial structure that matters. This is where the physics becomes richer and the challenge more formidable. To go beyond DMFT's mean-field approximation, theorists have developed cluster extensions of the method. In cellular DMFT (C-DMFT) or dynamical cluster approximation (DCA), instead of solving a single site embedded in a mean-field bath, one solves a small cluster of sites—say, 4, 8, or more neighboring sites—embedded in a mean-field bath. This approach retains some spatial correlations while remaining computationally tractable. By gradually increasing the cluster size, one can systematically improve the description and approach the complete solution. These cluster methods represent a crucial bridge between the simplicity of single-site DMFT and the full complexity of the interacting many-body problem, allowing researchers to capture spatial correlations and phase transitions that single-site approaches would miss. Deriving a prediction is wonderful, but how do you verify that you've actually reached the transition point in a real or simulated system? How do you distinguish with absolute certainty between the metallic and insulating phases? You need a clear, unambiguous signal—a quantum fingerprint that unmistakably identifies each phase. Deriving a prediction is terrific, but how do you verify that you've actually reached the transition point in a real or simulated system? How do you distinguish with absolute certainty between the metallic and insulating phases? You need a clear, unambiguous signal—a quantum fingerprint that unmistakably identifies each phase. There is a non-trivial phase marker that we can use: single-site entanglement entropy, a concept drawn from quantum information theory. This quantity measures something deeply quantum: the degree of uncertainty or "blurry" in the quantum state of a system. In particular, the entanglement entropy between one site in the material and all its neighbours quantifies how tangled and interdependent the quantum states are. In the metallic phase, when electrons are mobile and flowing freely, the state of any single site is profoundly uncertain. Is there an electron here? Maybe. Is the site empty? Equally probable. What is the spin orientation? Either up or down with equal likelihood. Is the site doubly occupied (if allowed by interactions)? All these possibilities are equally likely. This complete uncertainty, this maximum blurriness, yields a specific entanglement entropy value: the natural logarithm of four, or $\ln 4 \approx 1.386$ bits. This is the unique fingerprint of the metallic phase. But at the precise moment of the Mott transition—when the quantum traffic jam suddenly locks up —something remarkable happens. The blurriness evaporates instantaneously. The powerful electron repulsion renders double occupancy energetically catastrophic, effectively eliminating this possibility. Similarly, the empty state becomes highly unfavourable. Suddenly, each site can have only one electron, with spin either up or down. The four possibilities collapse to two. The entanglement entropy drops discontinuously to $\ln 2 \approx 0.693$ bits. The integration of information-theoretic quantities, such as entanglement entropy, with traditional condensed matter methods represents a new paradigm. We are witnessing the convergence of quantum information theory and materials physics, two once-separate fields that are increasingly revealing deep connections. Naturally, one question arises: Why does this matter? Understanding these principles is not merely an academic exercise. The broader implications stretch across condensed matter physics. A growing list of fascinating materials exhibits Mott-like behaviour: high-temperature superconductors, heavy fermion compounds, organic conductors, and materials displaying metal-insulator transitions driven by charge, spin, or structural degrees of freedom. Many of these materials promise revolutionary technologies—quantum computers, ultra-efficient electronics, new forms of energy storage—but we cannot design and optimize them without understanding the fundamental physics of their transitions. Perhaps most tantalizing: if we can now predict and fingerprint quantum transitions with this new precision, what else might we discover? We are not just learning to describe the quantum traffic jam anymore. We are learning to control it, to manipulate it, perhaps even to harness it for technologies we have yet to imagine. The 21st century may well be remembered as the age when humanity learned to engineer Mott transitions, and in doing so, unlocked a universe of quantum materials and mottronics-based technologies that transformed the technological landscape.

(*Ankur Majumder is a 4^{th} year PhD student in the department and a PMRF fellow*)

Physics News

Full simulation of a 50-qubit universal quantum computer achieved for the first time

A research team at the Jülich Supercomputing Center, along with NVIDIA's experts have fully simulated a universal Quantum Computer with 50 qubits for the first time, achieved at JUPITER Supercomputer in Germany. Simulating 50 qubits demands around 2 petabytes of memory, currently only provided in select supercomputers. The record was made possible by the close coupling of central processing units (CPUs) and graphics processing units (GPUs) in NVIDIA GH200 Superchips.

Awards and Recognitions

Prof. Ram Bilash Choudhary, has been honoured with the Jharkhand Best Teacher Award by the Indian Society for Technical Education (ISTE). The award was conferred at the Faculty Convention Centre, GGSESTC Bokaro, on October 31, 2025, in recognition of his outstanding academic performance and research contributions during the Monsoon and Winter semesters of the Academic Year 2024–2025. Heartiest congratulations to Prof. Choudhary on this well-deserved recognition!

Physics in History

- **8 November 1895:** Wilhelm Röntgen indeed discovered X-rays (which he called "X-radiation" to signify an unknown type of radiation) on this date while experimenting with cathode-ray tubes at the University of Würzburg. He won the very first Nobel Prize in Physics for this discovery in 1901.
- **9 November 1921:** Albert Einstein was awarded the 1921 Nobel Prize in Physics for the photoelectric effect, though the announcement was actually made retroactively on November 9, 1922. The committee had reserved the prize for a year before formally voting to honor him.
- **9 November 1994:** The chemical element Darmstadtium (Ds) was discovered at the GSI laboratory in Darmstadt, Germany.
- **13 November 1971:** The American space probe, Mariner 9, became the first spacecraft to orbit another planet successfully, swinging into its planned trajectory around Mars.

Prof. Bobby Antony has been awarded the Fellowship of the Institute of Physics (FInstP), a well-deserved recognition of his outstanding contributions to the field of physics.

Dr. Sk Riyajuddin has been appointed as an Editorial Board Member of Nature Scientific Reports. This recognition is a testament to his outstanding contributions to the field OF Material Science and Nanotechnology and his dedication to advancing scientific research.

Online Talk

Tanuj Datta participated in the international Scintillometry 2025 conference held at McGill University, Montreal, Canada, from 27–31 October 2025. He delivered his first contributed online talk on the multiwavelength study of LMXRBs as potential engines of globular-cluster FRBs, representing the research group of Prof. Esha Kundu.

International Visit

From October 22–29, 2025, Prof. Rajendra Prasad Giri and PhD scholar Ms. Suprita Paul visited the Indian Beamline at KEK, Japan, conducting advanced X-ray scattering studies on biomimetic cell surfaces with cholesterol and graphene nanoparticles.

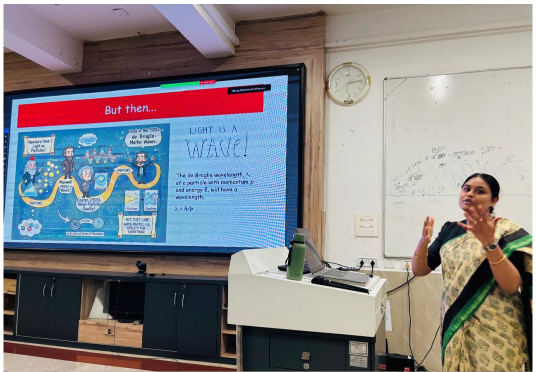
Their work explored how graphene alters membrane organization and its links to thermodynamics and cell-surface mechanics, using KEK's high-brilliance synchrotron facility. Ms. Paul also gained valuable hands-on experience in beamline operations and model membrane fabrication. The team gratefully acknowledges DST–KEK Collaboration (DST, GoI JNCASR) and IIT(ISM) Dhanbad for facility access and financial support. Access to the KEK synchrotron is highly competitive, granted only to projects of exceptional scientific merit.

Events Oraganized

The Global Initiative of Academic Networks (GIAN) course titled "Statistical Mechanics of Active Matter: Principles, Models, and Applications" was successfully conducted at the Indian Institute of Technology (Indian School of Mines), Dhanbad, from 6–11 October 2025. Organized under the Ministry of Education, Government of India, the course brought together participants from multiple institutions to explore the rapidly developing field of active matter. The week-long program offered a comprehensive introduction to the theoretical, computational, and experimental aspects of active matter, an interdisciplinary domain central to understanding collective behaviour in biological assemblies, synthetic active materials, and robotic systems. The course emphasized the growing relevance of active matter research to emerging applications in biotechnology, robotics, and materials science.

The lectures were delivered by Prof. Zhiwei Peng (University of Alberta, Canada) and Prof. Pankaj Mishra (Department of Physics, IIT (ISM) Dhanbad). The program also benefited from the expert contributions of Prof. Yashwant Singh, Distinguished Professor, Department of Physics, Banaras Hindu University (BHU), Varanasi. The course content covered topics spanning non-equilibrium statistical mechanics, kinetic theories of active systems, microscale and continuum modelling, rheology, numerical simulation techniques, and experimental approaches. Hands-on sessions and case-study discussions further enriched the learning experience and fostered productive academic interaction among the participants. The successful completion of these courses reflects the institute's ongoing efforts to promote advanced scientific training and international academic collaboration through the GIAN program.

A popular science talk was organized by the Society of Physics on October 23 in Raman Hall. The session was taken by Prof. Sudeshna Sen, who meticulously went through topics in both Classical and Quantum Mechanics. Prof. Sen began by giving a brief history of classical mechanics, followed by the dawn of quantum mechanics, explaining in such a simple, yet fruitful manner, to accommodate the variety of age groups, from curious first-year B.Tech students to experienced PhD scholars and veteran Professors of the department. A key feature of the talk was its exploration of Nobel Prize-winning research in quantum mechanics, including a discussion on the science and significance of this year's prize. Prof. Sen also emphasized the critical role of emerging quantum technologies and their growing relevance in both modern science and the commercial sector. The session wrapped up by opening the podium for questions, sparking a lively discussion as fellow professors posed insightful questions to Prof. Sen. The event was a resounding success, clearly achieving its aim of generating fresh interest in the fascinating field of quantum mechanics among all attendees.



Another Global Initiative of Academic Networks (GIAN) course on Astronomical Spectroscopy was successfully organised at IIT (ISM) Dhanbad, following its inauguration on 27th October 2025.

The course was conducted by Prof. Jonathan Tennyson, Department of Physics and Astronomy, University College London (UCL), UK, an internationally renowned expert in molecular spectroscopy and astrophysical modeling. The program was hosted by Prof. Bobby Antony, Department of Physics, IIT (ISM) Dhanbad.

Over the duration of the course, participants explored fundamental and advanced aspects of astronomical spectroscopy, including spectral line formation, molecular processes in astrophysical environments, high-resolution laboratory spectroscopy, and the interpretation of observational data from modern telescopes. The lectures and interactive sessions offered participants a comprehensive perspective on how spectroscopic techniques can be used to probe the physical and chemical properties of celestial objects.

The course attracted enthusiastic participation from students, research scholars, and faculty members across several institutions, fostering academic exchange and strengthening research exposure in the field of astrophysics. Participants appreciated the opportunity to engage directly with leading experts and gain insight into frontline research methodologies.

The Department of Physics extends its gratitude to the Ministry of Education, Government of India, for supporting this initiative through the GIAN program, and to Prof. Tennyson and Prof. Antony for their valuable contributions in making the course a success.

IBM's Qiskit Fall Fest 2025 was hosted in our campus from 27 October to 2 November. This week-long celebration marked the 100 years of quantum science. Organized by second- and third-year B.Tech students under the guidance of Prof. Sumit Kumar, the event brought together workshops, expert talks, interactive sessions aimed at introducing students to the world of quantum computing.

Throughout the week, participants attended hands-on workshops that provided an introduction to Qiskit, IBM's open-source quantum computing framework. The fest also featured talks and panel discussions by alumni and professionals in the field, offering deeper insights into the landscape of quantum technology and its future applications.

Physics Job Openings

Quantum Machines, is currently hiring Quantum Physicists (M.Sc., Ph.D., Post-Docs) for multiple global locations, including Australia, Boston (MA), California, Chicago (IL), Delft (Netherlands), Stuttgart (Germany), Japan, Korea, and Singapore. Interested candidates may send their CV directly to gilad.sivan@quantum-machines.co . The company's mission is to drive the next generation of quantum computing technologies.

Research Publications

1. **M. Abdullah, K. Khokhar, S. Bagchi**, M. N. Harakeh, H. Akimune, **D. Das**, T. Doi, L. M. Donaldson, Y. Fujikawa, M. Fujiwara, T. Furuno, U. Garg, Y. K. Gupta, K. B. Howard, Y. Hijikata, K. Inaba, S. Ishida, M. Itoh, N. Kalantar-Nayestanaki, **D. Kar**, T. Kawabata, S. Kawashima, K. Kitamura, N. Kobayashi, Y. Matsuda, A. Nakagawa, S. Nakamura, K. Nosaka, S. Okamoto, S. Ota, **S. Pal, R. Pramanik, S. Roy**, S. Weyhmiller, Z. Yang, and J. C. Zamora, Probing isoscalar giant resonances with multipolarity $L \leq 3$ in even-A neodymium isotopes, Physical Review C **112**, 044316 (2025).

2. **Poulami Das, Subhankar Nanda, Satyaranjan Satyajit, Jyotsna Patra, Amitava Adak**, Engineering intense laser-induced plasmonic structures on a solid nickel surface, Optics & Laser Technology **192**, 114066 (2025).

3. **A. Majumder and S. Sen**, Mott Metal-Insulator Transition in a Modified Periodic Anderson Model: Insights from Entanglement Entropy and Role of Short-Range Spatial Correlations, Advanced Theory and Simulations (2025): e01224.

4. Abhipsa Sekhar Biswal, **Nandeshwar, Umakanta Tripathy**, Soumit Chatterjee, Restoring epigenetic balance for glioma: Targeting IDH1_R132H with phytocompounds and tracking their efficacy under various pH conditions, International Journal of Biological Macromolecules **333**, 148571 (2025).