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EARLY INDIAN CONTRIBUTIONS TO QUANTUM THEORY

ARNAB RAI CHOUDHURI

When quantum theory was being developed during the first three decades of the 20th century (ultimately leading to the formulation of quantum mechanics), a small region of western Europe acted as the cradle for this new physics. The handful of physicists who worked on this new physics in a few centres of western Europe formed a closely-knit circle,

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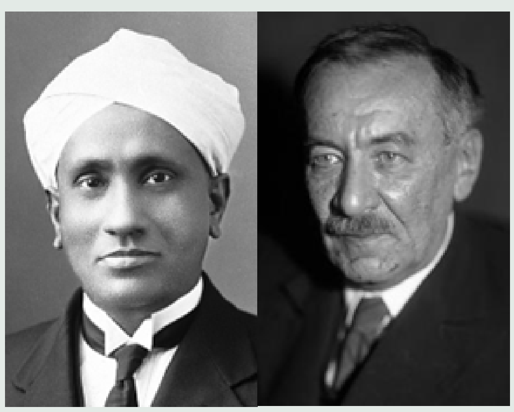
TWO CITIES BUT ONLY ONE NOBEL PRIZE
LIGHT SCATTERING AND QUANTUM MECHANICS

RAJARAM NITYANANDA



The hundredth birthday of quantum mechanics was celebrated at ICTS-TIFR in a meeting held between January 13-17 2025, now accessible at https://icts.res.in/discussion-meeting/QM100. This was almost entirely focused on contemporary and future developments. There was, however, room for a few presentations which looked back.

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HUGE DEPTHS IN QUANTUM MECHANICS REMAIN TO BE MINED AND UNDERSTOOD
A CONVERSATION WITH MICHAEL BERRY

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WHAT WERE ONCE PUZZLES IN THE FOUNDATIONS OF QUANTUM MECHANICS HAVE BECOME EXPERIMENTAL REALITIES
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REMEMBERING DR KRISHNASWAMY KASTURIRANGAN (1940–2025)

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DR KRISHNASWAMY KASTURIRANGAN (1940-2025)

BORN: OCTOBER 24, 1940 – ERNAKULAM, KERALA

DIED: APRIL 25, 2025 – BANGALORE

SPENTA R. WADIA

Dr Krishnaswamy Kasturirangan's passing away is a deep loss for India. He was a visionary scientist and institution-builder with a rare blend of idealism, pragmatism, and unwavering commitment to national progress. His guidance and advocacy shaped science, engineering, and education, in India in profound ways. His absence will be deeply felt—but his legacy will endure.

For over three and a half decades Dr Rangan (as he was affectionately called) was associated with India's space program, building on the legacy of Homi Bhabha, Vikram Sarabhai, Satish Dhawan and U. R. Rao. He played a pivotal role in India's lunar mission, key satellite missions and launches; initiated space based remote sensing applications for national development and basic sciences including AstroSat the multi-institutional Indian astronomy mission, which included the Tata Institute. After stepping down from the decade long Chairmanship of the Indian Space Research Organization in 2003, he served as an invited member of the Rajya Sabha and after that as a member of the planning Commission of the Govt of India (2009-14) overseeing policies and plans pertaining to science, technology, environment, and agricultural research.

A lot more can be said about the life and contributions of Dr Rangan to space, atomic energy, and to the TIFR system, but I will only reminisce about his role in the ICTS and also touch upon his role in the Draft National Education Policy (DNEP) 2019 and the National Research Foundation of India that was proposed in the NEP. An excellent account of Dr Rangan's life work can be found in the book "Space and Beyond: Professional Voyage of K. Kasturirangan", Edited by B. N. Suresh, Springer (2021).

ICTS-TIFR

Dr Rangan had been a member of the Governing Council of the Tata Institute of Fundamental Research (TIFR) since 2004. I first interacted with him in 2006, when I presented the idea of the International Centre for Theoretical Sciences (ICTS) to the Council. From the outset, he was deeply enthusiastic and fully committed to the vision. He strongly believed that India needed an institution like ICTS—an international meeting place for the theoretical and mathematical sciences.

Dr Rangan took ownership of the ICTS and of its three principal missions: Research, Programs and Outreach. The Council unexpectedly asked me to secure both funding and land for the institute. The financial component was manageable due to TIFR's association with the Department of Atomic Energy. The real challenge lay in acquiring land.

This is where Dr Rangan stepped in, not merely with verbal support but by enabling the actual pathway to the Vidhana Soudha (Karnataka State Legislature) in Bangalore. He introduced me to the key people in the Government of Karnataka. Despite many obstacles, the State Government eventually allocated approximately 78,000 square meters in Bangalore to ICTS in 2009. His interventions didn't stop there. When we faced delays in securing Kaveri water supply from the GKVK reservoir, he connected me with

A group photo of participants at the Consultation on National Education Policy, 2 December 2017

the relevant people who helped resolve the issue.

In ICTS's early years, I regularly presented progress reports—on infrastructure, approvals, programs, and faculty hiring—to the TIFR Council. Dr. Rangan's consistent support during these meetings was invaluable encouragement, especially given the scale of the task.

As a Member of the Planning Commission (2009–2014), he ensured that ICTS was explicitly mentioned in the Twelfth Five-Year Plan (2012–2017). This quelled my concerns that ICTS may not happen.

His pivotal support at key moments—including a crucial meeting on May 1, 2009, in Bangalore—was instrumental in securing the first 10 faculty positions and 7 administrative positions for ICTS. The request for a viable Centre was for 35 faculty positions over a period of time in a phased manner. There are countless such interventions, but suffice it to say: without Dr. Rangan, ICTS may not have come to be as it stands now. He remained deeply committed to its progress and growth. We were fortunate to have him visit ICTS a few times and in 2017 he delivered the ICTS Abdus Salam Memorial Lecture titled, "The Early Indian Space Endeavour: An Anecdotal Account".

NEP and NRF

I came to know Dr. Rangan even more closely during his tenure as Chair of the Committee to draft the National Education Policy (NEP). Dr Rangan considered, "the NEP as the mother of all his responsibilities", as mentioned to those who had worked closely with him.

On December 2, 2017, the Kasturirangan Committee organized a major NEP consultation at ICTS. Around this time, he formed the NEP Drafting Committee. One of the main challenges was to preserve its autonomy and have the committee work without `interference', and Dr Rangan agreed that ICTS would be a suitable place. The draft NEP was written at Ajanta House in ICTS between December 2017 and September 2018 by Manjul Bhargava, Anurag Behar, Kadayapreth Ramachandran, and Leena Chandran Wadia.

I had long been thinking about a "National Science Foundation of India". The drafting committee was also exploring a similar idea as part of the higher education section of the NEP. However Dr Rangan coined the term "National Research Foundation (NRF)", envisioning it as an inclusive body to support not just science and engineering but also the social sciences, arts, and humanities. Initially, this broad scope seemed ambitious, but over time, I fully appreciated its vision and necessity.

I later worked closely with Manjul Bhargava (Member NEP Committee) and K. VijayRaghavan, then Principal Scientific Advisor to Govt of India, to prepare the Detailed Project Report (DPR) for the NRF, in consultation with many eminent academics from India and abroad. Dr Rangan was very happy with the DPR when I showed it to him and made extensive comments on the way forward. Unfortunately, the final "Anusandhan National Research Foundation Bill 2023" that was passed in Parliament did not reflect some of the main points in the original DPR, and the spirit of the NEP. He was very unhappy about this but conceded that the NRF needed to come about, and hoped that improvements can be done in due course.

Spenta R. Wadia is the Founding Director and Infosys Homi Bhabha Chair Professor at ICTS-TIFR, Bengaluru.

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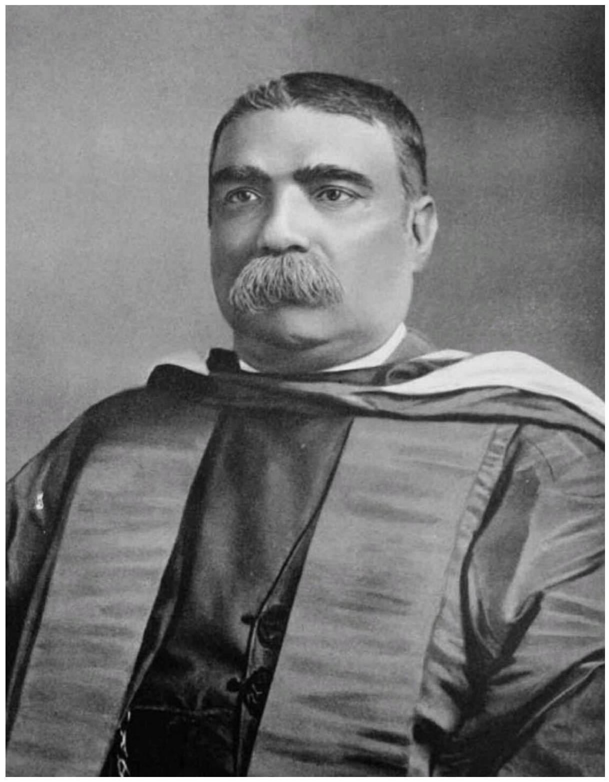
EARLY INDIAN CONTRIBUTIONS TO QUANTUM THEORY

ARNAB RAI CHOUDHURI

Of which the members knew each other well and had regular close interactions among themselves. It certainly did appear that an outsider in a remote land had very little chance of making an inroad into this charmed circle. The USA was already a fabulously wealthy country and was known as the land of inventors (from Bell to Edison). Still, young Americans like Oppenheimer, who wanted to contribute to the new physics, felt that they had to come to Europe for training in research.

Against this backdrop, it is really remarkable that three extraordinary discoveries came in the 1920s from an impoverished colony without any previous tradition of research in modern physics: Saha ionization equation (1920), Bose(-Einstein) statistics (1924) and Raman effect (1928). Perhaps the Compton effect discovered in the USA in 1923 was the only other discovery of that class pertaining to the new physics that was made outside western Europe during this tumultuous decade of the 1920s. It is often not realized how unique and unusual these physics contributions from India in the 1920s are in the annals of the history of science. It will be difficult to find another similar example from anywhere in the world in any branch of science: a succession of such extraordinary discoveries coming from a faraway peripheral land while a scientific revolution was at its peak.

Calcutta University, where the three discoverers had worked, was established in 1857 and was initially a body for conducting examinations and granting degrees without having its own faculty until Asutosh Mookerjee took over as Vice-Chancellor about half a century after its establishment. Mookerjee obtained fairly substantial donations from several wealthy Indians (lawyers like Taraknath Palit and Rashbehari Ghosh, as well as a few enlightened Maharajahs) to establish various academic departments and to start a few professorships. He laid down the foundation stone of the Science College of the University in 1914. Mookerjee himself was a brilliant mathematician, who had published a string of original papers in mathematics in leading journals at a very young age. As there was very little scope of a career in mathematics in India of that time, Mookerjee had to take up the legal profession before being



Sir Asutosh Mookerjee, who handpicked Raman, Bose and Saha for the new Physics Department of Calcutta University.

appointed to head Calcutta University. Although Mookerjee could not pursue mathematics research in his later life, he maintained a lifelong interest in mathematics and physics. He knew that it was an era of a revolution in physics and wanted to establish a Physics Department where there would be teaching and research in relativity and quantum theory. His well-wishers cautioned him that this was an absurd idea: there was nobody in the whole of India who even knew relativity and quantum theory.

The way Mookerjee built up the Physics Department can be stuff from a fairy tale. He knew of a 26-year-old officer in the Finance Department, who was passionate about physics and had already published about a dozen papers in top international journals by carrying on research in his spare time. Mookerjee wanted to get him for the most prestigious chair of the fledgling Physics Department — the Palit Professorship. However, Mookerjee could offer him only Rs. 600 against his salary of Rs. 1100. Would he be willing to take up this professorship? The young man, C.V. Raman, jumped at the offer.

Mookerjee also needed younger persons to man the department. As it happened, the batch which completed master's degree in the year 1915 was an exceptional batch. Mookerjee called three bright boys of that batch for a discussion. Only one of them, Sailen Ghose, was a student of physics. Although the other two, S.N. Bose and M.N. Saha, were students of mixed mathematics (what we would now call applied mathematics), Mookerjee knew that they were interested in physics. Mookerjee asked the three boys if they could teach the modern topics of physics which had never been taught in any Indian university so far. Saha was assigned to teach quantum theory and Bose was assigned to teach relativity. Sailen Ghose, who was a good experimenter, was given the job of designing the laboratory course and setting up the experiments.

Before classes started in 1916, there was trouble. Although Sailen Ghose managed to acquire various laboratory instruments and set up the laboratory, he could never formally join the department. He had connections with revolutionary groups fighting the British imperialism. Police found clues about this and raided his home when he was away. It appeared that he would be sent to the British penal colony of the Andaman Islands if caught. Ghose fled India in a ship bound for Philadelphia disguised as a Muslim crew member, thus putting down the curtains on what appeared to be a very promising career in physics.

Now we show a group photograph of the faculty members in the newly established Physics Department of Calcutta University taken around 1920. This happens to be the only existing photograph which has all three of our protagonists – S.N. Bose, C.V. Raman and M.N. Saha. Note that it was a rather small department consisting of only about a dozen faculty members. A few other eminent faculty members of the newly established Physics Department besides the famous trio can be seen in this photograph. Standing fourth from left is S.K. Mitra, who made fundamental contributions in the study of the upper atmosphere. Seated fifth from left is D.M. Bose, who along with his student Bibha Chowdhury, the first notable woman physicist of India, came very close to discovering the π-meson. It may be noted that S.N. Bose shifted in 1921 to Dacca University, where his famous work was done.

Since the Saha ionization equation, the Bose(-Einstein) statistics and the Raman effect have become textbook materials in advanced physics courses, we assume that all the readers of this article would know what these famous discoveries are about. We point out some curious historical facts connected with these discoveries which may not be so well known.

The physics faculty of Calcutta University around 1920. S.N. Bose, C.V. Raman and M.N. Saha are seated in the front row in the 1st, 3rd and 4th positions from left.

Saha ionization equation. Saha's work is a classic example of synthetic scientific research in which results from several different branches of science are combined together. Gibbs and Nernst had developed the theory of chemical equilibrium. When an atom breaks into an ion and a free electron, the process has some similarities with a chemical reaction. Eggert and Lindemann were the first to realize that the theory of chemical equilibrium can be adopted to the problem of ionization equilibrium. A primitive version of what we now call the Saha ionization equation can be found in their papers. However, in order to make quantitative calculations for the ionization of any particular chemical element, one needs to use the value of its ionization potential. Eggert and Lindemann had no idea how to do ionization calculations for any other elements besides hydrogen and could not proceed very far.

Saha was familiar with some atomic physics experiments and figured out correctly how to obtain the ionization potentials of several elements from the data of these experiments. Saha also realized that this theory can be applied to solve several outstanding problems of stellar spectroscopy. Stars of different colours were known to have different sets of spectral lines. Many astronomers wondered whether this indicated that stars of different colours had different chemical compositions. Realizing that the colours of stars indicated their surface temperature, Saha managed to calculate ionization levels at these different temperatures and was able to develop a fairly complete theory of stellar spectra. Rosseland wrote in his well-known 1936 textbook *Theoretical Astrophysics*:

The impetus given to astrophysics by Saha's work can scarcely be over-estimated, as nearly all later progress in this field has been influenced by it, and much of the subsequent work has the character of refinements of Saha's ideas.

What is the moral of the story? Saha mentioned on many occasions that during his younger years he had the habit of aimlessly reading about various scientific topics. Presumably, this reading habit made him familiar with several totally unconnected areas of science – chemical equilibrium theory, atomic physics experiments, stellar spectroscopy – which he combined brilliantly in his synthetic work. A scientist trained in research in the usual manner would specialize at an early stage and would not normally know a lot about such totally disconnected research fields. Saha might have been the only person in the world to know sufficiently about these very different subjects which he combined in his synthetic work! It is often said that the lack of formal training may occasionally help unusual creativity. Saha's case is certainly a clear example of this.

Bose(-Einstein) Statistics. In the famous 1900 paper which started the quantum revolution, Planck calculated the number of modes of blackbody radiation inside a cavity by classical arguments and then combined the quantum hypothesis with that. Many physicists found this mix of classical and quantum arguments somewhat unsatisfactory. Bose was the first person who could give a fully quantum derivation by considering the blackbody radiation to be a gas of photons and by finding out its number of states in the phase space, thereby initiating a new branch of physics: quantum statistical mechanics.

When Bose's small paper was rejected by *Philosophical Magazine*, he sent it to Einstein with a covering letter, asking Einstein whether he considered the paper worth publishing in a German journal. Einstein was so amazed by this paper from a stranger that he himself translated the paper into German and got it published in *Zeitschrift für Physik*. Bose had applied his statistical method only to particles like photons which have zero mass. Einstein was later able to generalize the method to include particles with non-zero mass, leading to what is known as the Bose-Einstein statistics.

Since Bose's paper was very tersely written and no copy of the original English paper which be sent Einstein is known to exist, certain historical concerns arise. To get the correct blackbody formula, it is necessary to multiply the phase space states by a factor of 2. Bose claimed to many persons in later life that he thought that this factor 2 was due to the spin of the photon, but Einstein changed it to polarization in his German translation. If Bose had indeed suggested the spin of the photon in 1924, then it was really remarkable because the electron spin was first postulated by Uhlenbeck and Goudsmit only in 1925. Although we do not have Bose's original paper, we have contemporary evidence that Bose really thought of the photon spin. In a 1931 paper, Raman and Bhagavantam had mentioned that Bose told them about his idea of photon spin.

There is another puzzle connected with Bose's work. An important ingredient of quantum statistics is indistinguishability of particles. Bose wrote down the correct formula for indistinguishable particles without mentioning indistinguishability anywhere in his paper! This gives rise to the question whether Bose fully understood the significance of the formula which he wrote down or whether he just happened to write down the correct formula by a lucky accident. Unless some hitherto unknown contemporary source material which throws light on this question is discovered, it is not possible to settle this question on the basis of materials available to us now.

Raman Effect. Saha and Bose made their famous discoveries at the age of 26 and 30 respectively, these being their first really notable works. On the other hand, Raman, who made his famous discovery at age 40, was already established for his works on acoustics and optics, and was already FRS. He was, however, viewed by many as somebody who was working on old-fashioned classical topics of physics. Curiously, it was he whose work provided an important experimental confirmation of the new quantum mechanics, verifying a theoretical prediction of Kramers and Heisenberg.

The Raman effect involves an inelastic scattering of a monochromatic beam of photons in which the photon energy either decreases or increases by an amount ΔE, producing feeble scattered radiation at two other frequencies. This energy shift ΔE corresponds to a difference in the energy levels of the molecules of the substance through which the monochromatic beam has been passing. Since a particular energy shift ΔE would be the signature of a particular molecule, the Raman effect was later developed into a powerful diagnostic tool for identifying and analyzing different substances.

A Russian group headed by Mandelstam also discovered the effect almost at the same time, leading to a priority dispute. Being aware that he was in a tight race, Raman used various strategies to win the race. Immediately after the discovery, Raman sent a short paper to *Nature*. Knowing that the publication in *Nature* may take a few weeks, he also got an account of the discovery printed quickly in *Indian Journal of Physics* which he had established barely a couple of years ago. Reprints of this paper were sent to many physicists around the world.

There has been another dispute: should K.S. Krishnan, Raman's student and co-discoverer, get more credit for the work than what he has been given? Although Krishnan did not have the habit of writing a diary regularly, he maintained one for a few weeks when he was working in Raman's laboratory – perhaps anticipating that they might come up with something big. On 9 February 1928, the day when Raman and Krishnan realized that they were on the threshold of a big discovery. Krishnan wrote:

> *When Prof[essor] returned after his walk he told me that I ought to tackle big problems like that... Told Mr Venkateswaran about the discovery and was discussing the problem with us, in the course of which he said that the phenomenon should be called the Raman-Krishnan-Effect.*

In 1928, a series of seven papers dealing with this discovery appeared in *Nature,* one after another. Except for the second paper, the other six papers had Raman and Krishnan as joint authors. In the second single-author paper, Raman wrote: "The preliminary visual observations appear to indicate that the position of the principal modified lines is the same for all substances" – a wrong statement which is not found in the other papers which had Krishnan as co-author! Presumably Krishnan, who was doing the experiments with his own hands, understood the significance of the discovery before his guru. Would it have been more appropriate to call this the Raman-Krishan effect? We leave this question to readers to ponder over.

Some materials in this article are taken from a two-part article in *Resonance* by the present author (*Resonance* **29**, 1557-1571, November 2024; *Resonance* **29**, 1689-1707, December 2024). I am grateful to the Editor of *Resonance* for permission to re-use these materials.

Arnab Rai Choudhuri is an astrophysicist with interest in the history of science, working at the Physics Department of IISc.

BETWEEN THE SCIENCE

RIDDHIPRATIM BASU was elected a Fellow of the Indian Academy of Sciences

BRATO CHAKRABORTI was awarded the Anusandhan National Research Foundation (ANRF), PM Early Career Research Grant

SUVRAT RAJU was elected a Fellow of the Indian Academy of Sciences

ICTS Endowed Visiting Professor **SRIRAM RAMASWAMY** was elected as an international member of the prestigious National Academy of Sciences (NAS) of the USA

ICTS postdoctoral fellow **PRATEEK ANAND** received the best poster award at the annual computational fluid mechanics conference, CompFlu-2024, held at IIT Hyderabad

ICTS graduate student **SOUVIK JANA** received an Honorable Mention in the Young Astronomer Award for the Best Publication by the Astronomical Society of India for the paper 'Cosmography Using Strongly Lensed Gravitational Waves from Binary Black Holes' published in the Physical Review Letters in 2023

ICTS graduate student **ADITYA SINGH RAJPUT** was awarded the pan-TIFR Sarojini Damodaran International Student Travel Fellowship

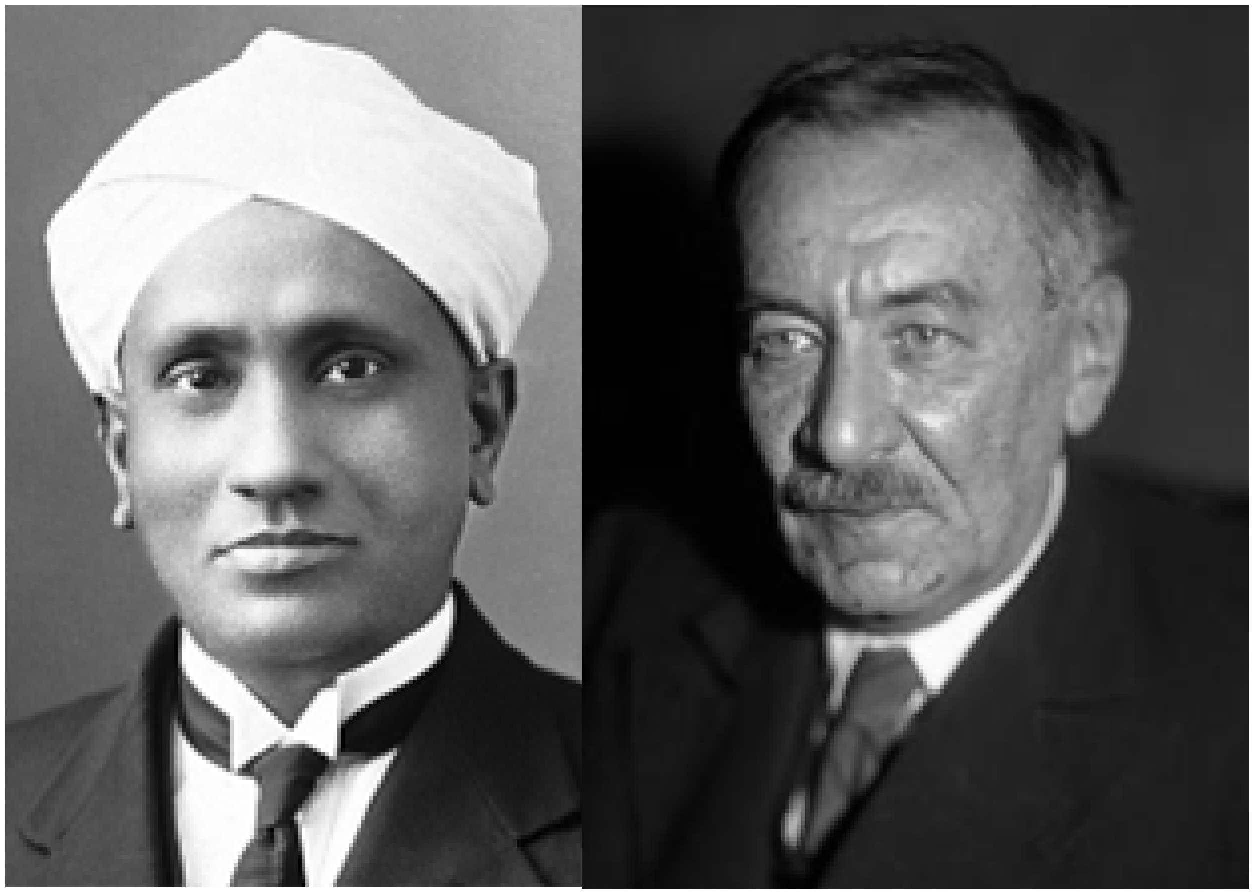
Former ICTS student **ADITYA VIJAYKUMAR** the 2024 Justice Oak Award for Outstanding Thesis in Astronomy by the Astronomical Society of India and the 2024 V.V. Narlikar Best Thesis Award by the Indian Association for General Relativity and Gravitation

RAJARAM NITYANANDA | *continued from Page 1 ...*

TWO CITIES BUT ONLY ONE NOBEL PRIZE: LIGHT SCATTERING AND QUANTUM MECHANICS

RAJARAM NITYANANDA

The scattering of light played a significant role in the extended birth years of the quantum theory, around 1923-1928. An additional reason for my reviewing light scattering in the meeting, and in this article, was the role of an Indian scientist, C.V. Raman. As is well-known, he received the 1930 Nobel Prize for, to quote the citation, "the effect named after him." The Raman Effect is quite simply, light encountering matter in any form and changing direction and frequency. The proportionality of frequency to energy is central to quantum mechanics. Today, we would view this process as simply energy and momentum exchange between matter and light. To understand why it had such a wide impact in its time, one has to focus on some of the events, ideas, experiments, and actors in this drama which unfolded in the 1920's.



CV Raman (left) and Leonid Mandelstam

Light which is refracted on entering a medium does not change its frequency, but does move more slowly. The microscopic explanation is that the atoms absorb and re-emit the incoming light, in a 'coherent' fashion. Coherence means that the total effect is co-operative – the scattered waves add to the incoming one and slow it down. The colours of the rainbow tell us that refraction depends on frequency. This phenomenon is called 'dispersion' since the colours are spread out by a prism or a raindrop. Quite surprisingly, the precise formula for how the refractive index varies with frequency was the topic of serious experimental and theoretical investigation and debate as late as 1923.

The reason is that Einstein had upset the applecart, in 1905 and again in 1917, by replacing light waves with discrete particles which we now call photons. In this situation it was very unclear to everyone, Einstein included, how one could recover even a familiar phenomenon as dispersion from basic principles. It appears that in this period, not only did light have a split personality, but induced this in physicists as eminent as Bohr, Kramers, and Slater. They were driven in their 1923 paper to give up the conservation of energy in individual microscopic events, while retaining it statistically, in their model which had an uneasy coexistence of waves and particles. This paper is only of historical interest today, but is worth reading to get a feel for the times.

In the same year, Adolf Smekal, in Austria, adopted Einstein's thermodynamic reasoning to assert that individual atoms would recoil when scattering the quanta of light, conserving energy and momentum. Further, he saw no reason why this energy exchange should be confined to the kinetic energy of the atoms motion, but could also involve the transition of the electrons between the energy levels which Bohr himself had given the world in 1912. In fact, this process was essential if one was not to disturb the well-known Boltzmann law giving the probabilities of different energy states. While persuasive, this reasoning had nothing to say about a wave phenomenon like dispersion.

This is the stage at which Kramers, who already had an earlier paper on dispersion, was joined by a young Heisenberg, and they undertook to revisit light scattering, incorporating the Smekal process without losing what was already known about dispersion. Their guiding light was the "correspondence principle", enunciated by Bohr, which was really a way of using classical mechanics to guess how a quantum system would behave. A formulation of classical theory which was very successful in celestial mechanics was brought to bear. This uses what are called 'action angle variables.' It suffices to say that even today, this topic represents the pinnacle of a graduate course on classical mechanics. With this tool in hand, Kramers and Heisenberg represented the atom as an assembly of entirely fictitious oscillators, coupled to an incident classical electromagnetic wave via dipole moments. In plain English, the electric field of the light acted to move positive and negative charges in opposite directions. After pages and pages of both algebra and argumentation, they obtained the amplitudes of scattered waves - both those of the same frequency – hence dispersion – and modified frequency.

However, they knew that the quantities entering this formula had no relation to a real atomic or molecular system. Waving the magic wand of the correspondence principle, they said laconically that 'one writes' ('man schreibt' in the original German!) a formula which had only the Bohr frequencies. These are differences of the energy levels. The strengths of the various terms were given by properties of their oscillators, which they could relate to the strengths of spectral lines in the Bohr theory. They recovered the earlier work on dispersion, but also calculated the strength of the processes Smekal had predicted in which the frequency of light changes by an amount proportional to the spacing between pairs of energy states.

Their January 1925 paper acquires additional interest in the context of Heisenberg's solo effort of July 1925. It is well-known that he proposed quantum mechanics, using matrices (which he re-invented for himself!) In his earlier paper with Kramers, the action variables on which the dipoles depended were continuous, and Fourier coefficients were discrete. The action variables become discrete as well once the correspondence principle is applied. In Heisenberg's formulation, *every* physical quantity, not just the dipole of the K-H paper, is represented by a matrix. The entries are labelled by two integers, referring to two energy levels. All trace of the original action angle variables and Fourier components has disappeared. He also dismisses the action angle theory in his introduction, noting that it does not describe the most general classical system.

It appears that the problem of light scattering set Heisenberg on the path towards quantum mechanics, once he removed the excess baggage. It is surely significant that he had to be alone to do this - his collaborators like Kramers or mentors like Bohr and Born might not have been as ruthless. Once he showed the way, of course, the world followed.

One person who followed very closely was Dirac, then a research student in Cambridge, who invoked another formulation of classical mechanics – Poisson brackets (often the section before action angle variables in the classical mechanics textbook!). He used these as a guide to writing down a general and self-contained theory by November 1925. Soon after, he went back to the problem of light scattering. By 1927, the machinery was all in place, and he applied the new mechanics not just to the atom, but to the electromagnetic field itself. He tersely concurs with the Kramers-Heisenberg formula, though of course not their derivation. The ghost of the dual nature of light should have been laid with this paper, though it continues to haunt many up to the present time.

This is the theoretical background to light scattering with change of frequency, also called inelastic light scattering. Experimenters do not wait for theorists to sort out their differences, but go ahead, driven by their own motivations. As early as 1922, C.V. Raman, in a review article, gave the example of specific heats to suggest, that Maxwell's theory had to be quantised. He was also impressed by the Compton effect, which showed clearly a frequency shift of an X-ray beam encountering free electrons. He and his students in Calcutta (as it was then) studied a large number of liquids, looking for systematic trends in their scattering behaviour, which might correlate with molecular properties, and reveal some quantum phenomena. His students Ramanathan and Venkateswaran saw early hints of frequency shifts.

In 1928, Raman put his outstanding student, K.S. Krishnan, onto the problem. By then, he was aware of the Kramers Heisenberg work. The clinching evidence came on February 28, 1928, from using a proper spectrograph and a mercury lamp. All the earlier work was with sunlight and filters. Raman lost no time in going to the press, and in mailing a thousand reprints of the discovery all over the world by the end of March.

The other protagonist is Leonid Mandelstam of Russia, eleven years older than Raman. He had spent 14 years in in the laboratory of F.K. Braun in Strasbourg, France, where he plunged into the new field of electronics, without taking his eye off the exciting physics happening in early 20th century Europe. Returning to his homeland in 1914, he struggled through the turbulent times of the Russian Revolution, even taking up factory jobs, till 1925 when he joined Moscow State University.

$$\mathfrak{M}(\nu-\nu^*) = R\,\frac{1}{4h}\left\{\sum_{R_a}\left(\frac{\bar{\mathfrak{A}}_2(\mathfrak{E}\mathfrak{A}_1)}{\nu_1+\nu}+\frac{\mathfrak{A}_1(\mathfrak{E}\bar{\mathfrak{A}}_2)}{\nu_2-\nu}\right)\right.$$

$$\left.+\sum_{R_b}\left(-\frac{\bar{\mathfrak{A}}_4(\mathfrak{E}\bar{\mathfrak{A}}_3)}{\nu_3-\nu}+\frac{\bar{\mathfrak{A}}_3(\mathfrak{E}\bar{\mathfrak{A}}_4)}{\nu_4-\nu}\right)+\sum_{R_c}\left(-\frac{\mathfrak{A}_6(\mathfrak{E}\bar{\mathfrak{A}}_5)}{\nu_5-\nu}-\frac{\bar{\mathfrak{A}}_5(\mathfrak{E}\mathfrak{A}_6)}{\nu_6+\nu}\right)\right\} e^{2\pi i(\nu-\nu^*)t} \quad (42)$$

which follow from (30), the result

$$P_r = E\frac{e^2}{h}\left|\Sigma_{J''}\left\{\frac{x_r(J'''J'')\,x_s(J''J')}{\nu(J''J')-\nu_s}+\frac{x_s(J'''J'')\,x_r(J''J')}{\nu(J''J')+\nu_r}\right\}\right|,$$

again in agreement with Kramers and Heisenberg.

Figure 1: (a) The Kramers Heisenberg formula of 1925 (b) Dirac's 1927 confirmation, using unrecognisably different methods – they differ only in notation (and the use of Gothic letters in (a))

Raman came into Calcutta University by invitation to a prestigious chair. In contrast, Mandelstam had to contend with a very well-established and conservative department at the Moscow State University and indeed struggled to even get subjects like relativity and quantum theory into the curriculum. Grigory Landsberg, eleven years his junior, was one like-minded colleague and they took up what had been his long-term quest. In 1918, Mandelstam had predicted that light falling on a crystal would scatter off the thermally excited sound waves which Debye had postulated in his theory of specific heats. This would cause frequency shifts depending in a precise way on the angle of scattering.

Leon Brillouin in France had independently and somewhat earlier predicted the same phenomenon, which is known as Brillouin scattering. Mandelstam was keen on searching for this effect experimentally and Landsberg joined him. The frequency shifts due to sound waves were rather small and barely resolvable with the equipment available to them at that time, but by 21 February 1928, they clearly saw scattered light with a much larger shift, both up and down, in crystals of quartz. They had better equipment than Raman but the light scattered by solids is much weaker than in liquids. There is no doubt that this pair were the independent co-discoverers of inelastic light scattering, but they did not seem to be in as much of a hurry as Raman was. The 1930 Nobel Prize went to C.V. Raman alone. This is not the place to speculate on the reasons, but we quote E.L. Feinberg, an academic descendant of Mandelstam.

"…the decisive factor was the delay in publishing the results. As we mentioned earlier in this paper, in his mature years Mandelstam not only strove ultimately to penetrate into 'the nature of things' but also to attain absolute confidence in his reasoning. That is why he tended to delay submitting his papers for publication until the moment when he felt that he had attained a faultless clarity presentation."

- E.L Feinberg

This is borne out by a study of the paper with Landsberg which finally appeared in *Zeitschrift fur Physik*, in May 1928, not that slow either! It clearly sets out the details of their experiment, and makes a comparison with the energy levels determined for the same crystal by infrared spectroscopy, which directly probes the crystal vibrations. It offers explanations for the dependence on the temperature and the wavelength of the incident light. In conclusion, they add a note that they have seen the same effect in calcite, and also cite a prior note by Raman and Krishnan in the journal *Nature,* commenting that it may be the same phenomenon but not enough details are given. By this time Raman's work was widely known and he and his group had reached similar conclusions for liquids and gases, strung out in a series of short papers. The wide acceptance of the Calcutta work may also owe much to the fact that the vibration frequencies of organic molecules can be used as a nice fingerprint of the bonds, so the effect is directly useful to chemists, who had to struggle with infrared work earlier. Indeed, by 1931, a major review article by R.W. Kohlrauch appeared in a prestigious series edited by Max Born and James Franck, with the title "Der Smekal -Raman Effekt". Smekal's name did not catch on but Raman is now an adjective, attached to microscopes, and to various later kinds of scattering of laser light which came much later. CARS for "Coherent Antistokes Raman Spectroscopy," which is used by biologists, is just one example.

Mandelstam was later also associated with the Physics Institute of the Academy of Sciences (also called the Lebedev Institute). He was recognised and highly regarded as the founder of an entire school of theoretical physics in Russia which was in some sense parallel to the better-known Landau school. His immediate descendants, Rytov, Andronov, and Leontovich went on to found schools themselves, in, nonlinear oscillations, radiophysics (which became laser physics) and plasma physics. Another descendant, Igor Tamm, went on to win a Nobel Prize himself and importantly, had further descendants like Ginzburg and Sakharov and others whose names are very familiar to theoretical physicists. One missed Nobel Prize pales into insignificance against such a 'gharana' (a term used for a school of music in India)

Returning to Raman, he moved to the Indian Institute of Science in Bangalore in 1933, and turned his attention to the crystalline state. One outstanding discovery was the behaviour of the Raman Effect in the same quartz crystal that Landsberg and Mandelstam had studied. His student Nedungadi heated the crystal close to its transformation to another form. One set of vibrations grew slower and ultimately 'froze' to give the new crystal structure. This was the first example of a 'soft mode' which underlies many such transformations.

Raman was always fascinated by diamond. The world's best data at that time on the very weak, so called 'second order' Raman spectrum of diamond came from his student R.S. Krishnan.

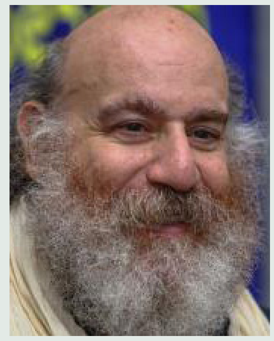
However, Raman's explanation of this result was flawed. The correct explanation came from faraway Edinburgh where Max Born and Mary Blackburn carried out extremely elaborate calculations of six continua of vibrational modes, without the aid of modern computers. In those days, a 'computer' was a person, often a woman with the patience and diligence to handle long numerical calculations with thousands of steps, without a single mistake! One strong motive was surely Raman's sharp criticism of Born's formulation of the vibrations of crystals. Looking back, one would think Born could have ignored the criticism since he was on strong theoretical ground. It seems, however, that he felt compelled to show that his theory fitted the experiments, with the added pleasure that they were carried out by Raman's pupil.

This misadventure aside, Raman's period in the Indian Institute of Science saw many of the major physicists of post-independence India pass through as students. Interestingly, there is not a single paper of Raman's where I could identify an equal collaborator – he was always the inspirer and the mentor, and if a student did independent work, it was published independently.

In conclusion, the theory of inelastic light scattering played a significant role in the birth of quantum mechanics, particularly influencing Heisenberg. The experimental realisation continues to be an important tool to the present day, sharpened by advances in lasers and instrumentation. The two main protagonists on the experimental side, Raman and Mandelstam, later had a very strong influence on physics in their own countries, with very contrasting styles.

Rajaram Nityananda is ICTS Endowed Professor of Physics at ICTS-TIFR, Bengaluru. He was formerly the Director of the National Centre for Radio Astrophysics (NCRA) in Pune and later of the Tata Institute of Fundamental Research (TIFR) Centre for Interdisciplinary Sciences in Hyderabad.

WILLIAM BIALEK ELECTED TO AAA&S



ICTS International Advisory Board member William Bialek has been elected to the prestigious American Academy of Arts and Sciences (AAA&S). https://www.amacad.org/new-members-2025

Prof. Bialek has made pioneering contributions to biological physics and chaired a committee constituted by the National Academies of Science, Engineering, and Medicine (USA) on the Decadal Survey of Biological Physics/Physics of Living Systems. He played a key role in the recognition of biological physics as a field of physics, alongside more traditional fields of physics.

ICTS congratulates Prof. Bialek for this recognition.

MICHAEL BERRY | *continued from Page 1 ...*

HUGE DEPTHS IN QUANTUM MECHANICS REMAIN TO BE MINED AND UNDERSTOOD

A CONVERSATION WITH MICHAEL BERRY

Michael Berry is Melville Wills Professor of Physics (Emeritus) at the University of Bristol, UK. He is a theoretical physicist renowned for his work in the intersections between classical and quantum physics. He is best known for discovering the geometric phase, often referred to as the 'Pancharatnam-Berry phase', when a system is subjected to cyclic adiabatic processes. The geometric phase has applications across various fields of wave physics. His awards include the Maxwell Medal and the Dirac Medal from the Institute of Physics, the Royal Medal from the Royal Society, the Pólya Prize from the London Mathematical Society, the Wolf Prize, and the Lorentz Medal. He received a knighthood in 1996. Prof. Berry spoke to Debdutta Paul on his recent visit to ICTS-TIFR for the 'A Hundred Years of Quantum Mechanics' program.

What is the status of the foundational questions in quantum mechanics now?

I have no idea. I don't work on them. I have a slightly negative view about attempts to, as people say, "interpret" or "understand" quantum mechanics. There are different formulations: you have the Schrödinger equation, you have the Heisenberg's matrices, you have Feynman's path integrals, you have Wigner functions, and then you have Many-worlds, Copenhagen, and so on. Now, I think the fact that quantum mechanics agrees so well with experiments means we already, in a sense, *understand* it.

Transport the question back to classical mechanics. Two points. Is Newton's equation more fundamental than Hamiltonian's? Philosophers could argue about it. In fact, Newton's equations are more general, that's another matter. But basically, it's an idle question: in relevant examples, they're equivalent. Nevertheless, classical mechanics is deeply mysterious. You ask somebody in the street, they would say: Why should the motion of planets and particles in mechanics be governed by second-order differential equations? It seems very abstract. People say the same about quantum mechanics. The mathematics is slightly less familiar, but now we understand it pretty well. So, it's a matter of what you get used to. There's a paper by Christopher Fuchs and Asher Peres with the wonderful title *Quantum Theory Needs No 'Interpretation'*.

There is a positive way to think of some of these investigations. Quantum mechanics is certainly false. It's absurd to think that in a few hundred years, a recently evolved species on a little planet somewhere, a long way from the centre of a galaxy, would have found the secret of the universe. It's nonsense. It is, of course, a very good theory, but it will surely one day be revealed as a special case of something deeper. Just as, for example, classical mechanics is a special case of quantum mechanics with appropriate subtleties. So, of course, one can then ask: What's a promising way to understand what lies beneath quantum mechanics?

The situation is very different from a hundred years ago when people were understanding what is beneath classical mechanics — that the answer is quantum. Different because then there were experiments all the time. I recently read a biography of Heisenberg. Almost every month, he learned about a new experiment and factored it into the matrix mechanics he was developing. Unfortunately, now there are no experiments that show that quantum mechanics is wrong. We have ideas where they might be wrong, like black holes, but we can't do experiments. So, the situation is different now. One day, I'm sure there'll be something fundamentally incompatible with quantum mechanics. It may have to do with its discordance with gravity. So, the positive aspect is getting beneath quantum mechanics. The negative aspect is we don't have experimental guidance.

Over the last couple of days, we have been hearing about quantum computations and quantum information. Will quantum computers be a functional reality soon?

I don't think so. I don't work in this area, but my colleagues in quantum information do. We heard here that quantum information is much broader than a quantum computer. There are already applications of quantum information, even though we don't have a quantum computer. As I've learned here, there will be quantum computers sometime, but the problems of scientific interest that quantum computers might solve are, at the moment, not very extensive. Quantum information is, however, a wonderful subject. I would put it this way: we know very little about the Hilbert space of more than two particles. That's incredible! There are huge depths in quantum mechanics yet to be mined and understood. This understanding will transform the world in the way that quantum mechanics has already transformed it.

Can you tell us about your work on the geometric phase in quantum mechanics? How do you see its significance evolving in modern physics and technology?

When I wrote my paper, I was ignorant of many relevant earlier works. I had more or less the complete story, but there were many precursors. In India, of course, there is S. Pancharatnam, who I admire enormously. I had never heard of him. I knew all the other members of the brilliant Raman family, except Raman himself, who had died, and Pancharatnam, who had died. When I found the geometric phase, I thought it was some interesting little tweaky corner of quantum mechanics, but my colleague John Hannay said, “No, this is going to be important.” I didn’t understand that, and I haven’t followed all the applications because my interests have shifted. I’m somebody who, having started something — it’s happened several times in my career — having started something and more or less laid the foundations, I’m not very interested in pursuing it. Of course, I’m pleased to see these advances, especially with the geometric phase curvature, because I regarded that as the most interesting part of what I did in the 1980s. I’m pleased to see this playing a role in condensed matter physics — topological matter has curvatures appearing everywhere — but it wasn’t something I anticipated.

What do you think will shape the future of quantum mechanics in the next century?

Well, that’s an interesting question. Of course, there’s this vast Hilbert space, but there is an elephant in the room, and this is a good opportunity to speak about it.

In the 1920s, Dirac said we understand the whole basis of chemistry. Most chemists, even today, don’t use quantum mechanics, but quantum chemistry is still a thriving subject, so Dirac was surely right. Now, we physicists like to boast that quantum mechanics explains all matter, at least the kind of matter that we see on this planet, at these temperatures and pressures and so on. Think of the Quantum Hall Effect, topological matter, and quantum phase transitions — so many things understood. But the elephant in the room, and I mean this literally, is that on this planet, a lot of matter is *alive*.

Where is aliveness in quantum mechanics? I don’t speak about quantum biology, a beautiful subject concerning specific biological processes — photosynthesis, where we harvest sunshine; magnets in the heads of birds that help them navigate. Do these depend on quantum mechanics for their existence? Does quantum mechanics enhance them over what you would find classically? Does quantum mechanics inhibit them? These are wonderful questions, but the fundamental question is *aliveness*. Where is it in the gigantic Hilbert space of even the smallest living organisms, plus rules for interacting with the environment? It has to be there somewhere. Schrödinger, of course, raised the question and made some attempts, which accelerated modern molecular biology, but not the question as I’m asking it. Some very subtle correlation between different bits of the Hilbert space? We just don’t know. So, I think that’s an elephant in the room. I don’t doubt that it’s there. I’m not a vitalist, so this means there is a lot of matter that we don’t understand. In the coming century, I see this coming into sharper focus.

Right, you’re talking about the phenomenon of emergence?

Yes. There are many emergent phenomena, and a lot of my work has been concerned with this aspect. Now, there are aspects of emergence that are endlessly discussed by philosophers. How can one theory contain another at a different level of description? They miss a central mathematical point. Very often, certainly in physics, this is when some parameter gets small or large. For example, the number of degrees of freedom gets large, Planck’s constant gets small, and in fluid mechanics, viscosity goes to zero: it’s a singular limit because when the viscosity gets small, you get turbulence, which is unanticipated. Many phenomena in quantum mechanics involve singular limits: as you go towards a classical limit, there is the random-matrix distribution of energy levels and so on. The point is that interesting limits in physics are *singular*. It means that living in the borderlands are phenomena that were not envisaged. This is emergence. It’s a *mathematical* problem. Different techniques are being developed in different areas. Asymptotic semi-classical techniques, renormalization in thermodynamics and statistical mechanics, where the number of particles is large — and so on. Life is, of course, an emergent phenomenon, but that doesn’t mean we can’t understand it. We need some analogue of renormalization or asymptotics, as yet unimagined.

Coming to the random-matrix theory, why are the predictions of random-matrix theory so robust in spite of the microscopic world, the physical systems in that world and their interactions being so very different from random matrices?

Well, exactly, and that’s work we did also in the 1980s (around the same time as the geometric phase). Universality in random-matrix theory, as applied to quantum systems with chaotic classical counterparts, comes from *classical* universality. That’s the origin of it.

And that classical universality concerns the distribution of very long periodic orbits, as I described in my talk. There’s a sum-rule from John Hannay and Ozorio de Almeida which has this intuition underlying it:

You take a given energy and one long periodic orbit; it will wind in a complicated way around the energy surface. Take all of them. There are exponentially many. They will cover the energy surface with the slightest coarse-graining, uniformly with a microcanonical distribution. And that *classical* sum-rule underlies the universality of random-matrix theory when applied to Gutzwiller’s trace formula for the density of energy levels of a quantum system, which is chaotic. It’s a sum over the periodic orbits of the system, and it’s the long orbits that determine random-matrix theory. And that’s why it’s robust: because it’s universal.

Random-matrix theory has its limits. Over long ranges of correlations, random-matrix theory is false, not universal because short periodic orbits are different from system to system. They don’t cover the energy surface uniformly. So, you can’t use that sum rule. We understand this now. It’s a question of more refined asymptotics. If you look at nearby levels over a range (and we know exactly in terms of Planck’s constant, how big that range can be), random-matrix theory works; it’s marvellous and universal. But if you go outside that range and are still semi-classical, still small compared to where you are in the spectrum, then the correlations which are sensitive to long ranges, like the pair correlation and so on, are not universal. They differ from system to system.

Is there any deeper reason for the universality to hold for long periodic orbits?

Yes, it’s the Heisenberg uncertainty principle. It’s the rule that large energy ranges correspond to short orbits, which are different from one system to another. So you don’t have the astonishing unanticipated fact that at shorter ranges, you get universality.

What can the modern point-of-view of doing quantum many-body physics and quantum information science using gate-based circuits learn from classic random-matrix theory?

I don’t know. I don’t know how to talk about things that I don’t know about.

Do you have any advice for people who work in this field or who aspire to work in this field?

Yes. I have two contradictory pieces of advice for people who ask me for career advice.

The first piece of advice is: don’t take advice.

But, if pressed, I would say that if I were starting out, I would probably work on quantum information. Probably, though I can’t tell — this is what philosophers call counterfactual history. So I would say: work on quantum information. There are so many riches to be uncovered there to do with these big Hilbert spaces, even with a modest number of particles. So that’s what I would say.

PETER ZOLLER | *continued from Page 1 ...*

WHAT WERE ONCE PUZZLES IN THE FOUNDATIONS OF QUANTUM MECHANICS HAVE BECOME EXPERIMENTAL REALITIES

A CONVERSATION WITH PETER ZOLLER

Peter Zoller is a professor and scientific director at the Institute for Quantum Optics and Quantum Information (IQOQI), University of Innsbruck, Austria. He is a theoretical physicist renowned for his pioneering contributions to quantum optics and quantum information. Prof. Zoller is best known for his theoretical proposals for using trapped ions and ultracold atoms as quantum systems. He has earned several prestigious awards, including the Wolf Prize in Physics and the Max Planck Medal. Prof. Zoller spoke to Debdutta Paul on his recent visit to ICTS-TIFR.

What do you think is the status of the foundational questions in quantum mechanics?

Many foundational aspects of quantum mechanics are related to entanglement, such as the EPR paradox and Schrödinger's cat, among others. Initially, these concepts were discussed as Gedankenexperiments (thought experiments), but the game-changer was transitioning them into the realm of experimental physics. Testing Bell inequalities to explore quantum correlations and entanglement over large distances is one example. Another is building and scaling quantum computers, which essentially involves creating Schrödinger's cats of increasing size in the laboratory.
So far, the evidence consistently shows that quantum mechanics, as we currently understand it, holds true even as we test and apply it to increasingly macroscopic quantum phenomena. What were once puzzles in the foundations of quantum mechanics have become experimental realities in laboratories and have paved the way for novel applications and quantum technologies.

However, at some level, certain aspects of quantum mechanics remain puzzling. A key example is the measurement problem, where we assume a divide between the microscopic quantum world and the macroscopic classical world.

And has there been any real progress along those lines recently?

You mean, in the sense of resolving this with experiments?

Experiments to understand how to resolve those paradoxes, such as the measurement problem.

While we have gained a much deeper theoretical and technical understanding of measurements — for example, reading qubits on a quantum computer — the fundamental question has remained unchanged.
Quantum optics has made significant contributions in this area. In experiments pioneered by Haroche and Wineland, single quantum systems were prepared and observed continuously, yielding single measurement trajectories. On the theoretical side, continuous measurement theory has been developed to answer questions such as: given a photon count trajectory observed in a single run of a laser-driven atom experiment, what can we infer about the dynamical evolution of the atom? This foundational work underpins our understanding of qubit readout in quantum computers. On a technical level, we have achieved a profound understanding. However, I am less certain that this progress has brought us closer to solving the measurement problem itself.

Right... you mentioned quantum computers. Will they be a functional reality soon?

We currently have small-scale quantum computers in our laboratories. However, they need to grow significantly to become truly useful and fulfil their potential. A recent major advancement has been achieving error correction at the breakeven point, bringing us closer to fault-tolerant quantum computing — as reported by the recent Google experiment. The big open challenge is scaling up, and certain platforms may prove more promising than others. It will undoubtedly be a very long journey, but I firmly believe that, in the end, there will be a fully functional quantum computer.

There's an obvious analogy with artificial intelligence. The basic ideas behind AI were developed 30, 40, or even 50 years ago.
At that time, the necessary hardware was unavailable, and it took a long time for the technology to catch up. But what eventually emerged has been amazing and has exceeded our expectations. My personal feeling is that quantum computing will follow a similar trajectory. We need to wait for the hardware to advance, but I am confident that it will happen.

With the boundary between quantum many-body physics and quantum information science getting increasingly blurry, what are the most important questions that straddle the fields?

A significant part of modern many-body physics focuses on understanding entanglement, from the classification of phases in condensed matter physics to scrambling and thermalization in non-equilibrium dynamics. Naturally, as soon as you mention the word “entanglement,” you are essentially talking about quantum information. Quantum information has firmly established itself as the language for describing these phenomena.

We now have quantum simulators in our laboratories, enabling us to study such questions through synthetic quantum matter. Once you begin asking questions about entanglement, you are talking about quantum information.

In a broader context, achieving quantum advantage for a meaningful problem remains a central question driving the field. On the technical side, error correction in large-scale devices, such as hardware-aware error correction strategies to manage the substantial overhead, is a critical area of focus.

The current noisy intermediate-scale quantum (NISQ) devices that we have are quite noisy, but what are the opportunities for discovering novel phenomena that they present that we don’t have with conventional solid-state experiments?

Condensed matter and solid-state physics focus on synthesising quantum materials and studying their properties. In contrast, quantum simulators, as Noisy Intermediate-Scale Quantum devices, enable us to create and study artificial or synthetic quantum matter, offering insights that are both beyond and complementary to traditional condensed matter experiments. Today, we have learned to build NISQ devices in laboratories as faithful experimental representations of complex many-body problems. These devices allow us to explore the properties of many-body systems, often surpassing the capabilities of classical computational simulations.

Entanglement is a central feature of all these studies. With quantum simulators, we are realising Feynman’s vision to build controlled quantum devices to “solve the quantum many-body problem,” accounting for large-scale entanglement.

Besides the practical and engineering challenges, what are the fundamental physics challenges to building full-fledged fault-tolerant quantum computers? In other words, what kind of fundamental physics progress will accelerate the field?

There are different paradigms of quantum computing. The quantum logic network model is the most widely pursued approach in today’s experiments. In this framework, we use qubits as quantum memory, quantum gates acting on these qubits, and readout mechanisms, and we have well-established methods for error correction.

However, there are alternative approaches to quantum computing. One example is measurement-based quantum computing, which has been explored far less in experimental settings. This paradigm involves preparing a cluster state — a highly entangled initial state — and performing measurements on the system to represent a quantum computation. Ultimately, this approach is equivalent to the quantum logic network model. Certain quantum hardware, such as photonic systems, may be better suited to this paradigm. Another promising approach is topological quantum computing, which is one of the most elegant methods for error-tolerant quantum computing. However, its experimental development is still in its infancy. We are only at the beginning of exploring and implementing these alternative, potentially promising forms of quantum computation.

What areas in science and industry do you see benefiting from all these investigations on quantum simulations and quantum computation?

The first obvious answer is that quantum computers will be useful in physics as quantum simulators, providing insights into new materials and phase diagrams. We can even reverse the question and ask: given a list of desired properties, can we use quantum simulators to design novel quantum materials? Through experiments with these quantum devices, we “learn” the relevant Hamiltonians, which can then be passed on to our chemistry colleagues in the hope that they can synthesise the corresponding real materials. This approach also extends to quantum chemistry and the design of new drugs. A large-scale quantum computer might also enable us to explore heuristic algorithms. Quantum optimization is one promising example in this area.

Finally, there are other applications, such as in quantum communication or in developing entangled quantum sensors that achieve precision beyond what is possible with uncorrelated particles.

What are the questions that will shape the future of quantum mechanics in the following century?

Quantum computing explores quantum mechanics by building larger and larger quantum systems, pushing the boundaries between the microscopic and macroscopic realms. This approach is quite different from the traditional path of studying quantum physics by investigating smaller and smaller scales, as in high-energy physics.

An exciting intersection lies at the interface of gravity and quantum physics, which we can explore by building quantum computers and testing quantum mechanics at this new frontier.

It is a win-win situation: either our quantum computers will scale and perform as expected, or we will uncover new physics waiting to be discovered.

PROGRAMS

Quantum Many-Body Physics in the Age of Quantum Information
25-29 November 2024 ✦ *Organizers* — Subhro Bhattacharjee, Manas Kulkarni, Sthitadhi Roy (ICTS-TIFR, Bengaluru) and Subroto Mukerjee (IISc, Bengaluru)

ICTS Workshop on HDXs and Codes
28 April-9 May 2025 ✦ *Organizers* — Irit Dinur (Weizmann Institute of Science Rehovot, Israel), Venkat Guruswami (University of California, Berkeley) and Prahladh Harsha (TIFR, Mumbai)

Radio Cosmology and Continuum Observations in the SKA Era: A Synergic View
7-18 April 2025 *Organizers* — Suman Majumdar (IIT Indore, India), Abhirup Datta (IIT Indore, India), Ilian T Iliev (University of Sussex, UK), Mark T Sargent (ISSI, Switzerland), Dharam Vir Lal (NCRA-TIFR, India), Nirupam Roy (IISc, India), Tirthankar Roy Choudhury (NCRA-TIFR, India), Girish Kulkarni (TIFR, India), Narendra Nath Patra (IIT Indore, India) and Saurabh Singh (RRI, India)

Beyond the Horizon: Testing the Black Hole Paradigm
24 March-4 April 2025 ✦ *Organizers* — Sumanta Chakraborty (IACS, Kolkata) and Sudipta Sarkar (IIT Gandhinagar)

Decisions, Games, and Evolution
10-21 March 2025 ✦ *Organizers* — Sagar Chakraborty (IIT Kanpur), Vishwesha Guttal (IISc, Bengaluru), Sandeep Krishna (NCBS, Bengaluru) and Supratim Sengupta (IISER Kolkata)

New Trends in Teichmüller Theory
24 February-7 March 2025 ✦ *Organizers* — Krishnendu Gongopadhyay (IISER Mohali), Subhojoy Gupta (IISc, Bengaluru), Kenichi Ohshika (Gakushuin University, Japan) and Athanase Papadopoulos (CNRS and University of Strasbourg, France)

Positive Geometry in Scattering Amplitudes and Cosmological Correlators
10-21 February 2025 ✦ *Organizers* — Nima Arkani-Hamed (IAS Princeton, USA), Johannes Henn (MPI Physics, Germany), Suvrat Raju (ICTS-TIFR, Bengaluru) and Jaroslav Trnka (UC Davis, USA)

Quantum Trajectories
20 January-7 February 2025 ✦ *Organizers* — Michel Bauer (IPhT, CEA Saclay, France), Cedric Bernardin (National Research University Higher School of Economics, Moscow, Russia), Raphael Chetrite (Université Côte d'Azur, Nice, France) and Abhishek Dhar (ICTS-TIFR, Bengaluru)

ICTP-ICTS Winter School on Quantitative Systems Biology
6-17 January 2025 ✦ *Organizers* — Stefano Allesina (University of Chicago, USA), Akshit Goyal (ICTS-TIFR, Bengaluru), Jacopo Grilli (ICTP, Italy) and Meghna Krishnadas (NCBS, Bengaluru)

Hearing Beyond the Standard Model with Cosmic Sources of Gravitational Waves
30 December 2024-10 January 2025 ✦ *Organizers* — Koushik Dutta (IISER Kolkata), Tathagata Ghosh (HRI, India), Anish Ghoshal (University of Warsaw, Poland) and Subhendra Mohanty (IIT Kanpur)

Indo-French Workshop on Classical and Quantum Dynamics in out of Equilibrium Systems
16-20 December 2024 ✦ *Organizers* — Abhishek Dhar (ICTS-TIFR, Bengaluru), Manas Kulkarni (ICTS-TIFR, Bengaluru), Satya N. Majumdar (LPTMS, France), Gautam Mandal (TIFR, Mumbai), Alberto Rosso (LPTMS, France) and Gregory Schehr (LPTHE, France)

Combinatorial Methods in Enumerative Algebra
2-13 December 2024 ✦ *Organizers* — Angela Carnevale (University of Galway, Ireland), Uri Onn (Australian National University, Canberra), Amritanshu Prasad (IMSc, Chennai), Pooja Singla (IIT Kanpur) and Christopher Voll (Bielefeld University, Germany)

DISCUSSION MEETINGS

Lean for the Curious Mathematician
24-26 April 2025 ✦ *Organizers* — Siddhartha Gadgil (IISc, Bengaluru), Ashvni Narayanan (University of Sydney, Australia) and T. V. H. Prathamesh (Krea University, Andhra Pradesh)

10th Indian Statistical Physics Community Meeting
23-25 April 2025 ✦ *Organizers* — Ranjini Bandyopadhyay (RRI, Bengaluru), Abhishek Dhar (ICTS-TIFR, Bengaluru), Kavita Jain (JNCASR, Bengaluru), Rahul Pandit (IISc, Bengaluru), Sanjib Sabhapandit (RRI, Bengaluru) and Samriddhi Sankar Ray (ICTS-TIFR, Bengaluru)

Discussion Meeting on Neuroscience, Data Science and Dynamics
21-23 April 2025 ✦ *Organizers* — Amit Apte (IISER, Pune), Neelima Gupte (IIT Madras, Chennai) and Ramakrishna Ramaswamy (IIT Delhi)

A Hundred Years of Quantum Mechanics
13-17 January 2025 ✦ *Organizers* —Abhishek Dhar (ICTS-TIFR Bengaluru) and Rajesh Gopakumar (ICTS-TIFR Bengaluru)

LECTURE SERIES

DISTINGUISHED LECTURES

Are We Living in the Matrix? What Quantum Experiments Reveal About the World and Our Powers in it, and What the Future May Hold
27 January 2025 ✦ *Speaker* — Howard Wiseman *(Griffith University, Brisbane, Australia)*

INFOSYS-ICTS TURING LECTURES

Dynamical Systems and Artificial Intelligence Applied to Data Modelling in Biological Problems
21 April 2025 ✦ *Speaker* — Gabriel Mindlin *(University of Buenos Aires, Argentina)*

FOUNDATION DAY LECTURES

Two Paradoxes in the Theory of Games
27 December 2024 ✦ *Speaker* — Deepak Dhar (ICTS-TIFR, Bengaluru)

PUBLIC LECTURES

The Six Faces of Subrahmanyan Chandrasekhar
29 October 2024 ✦ *Speaker* — Rajaram Nityananda *(ICTS-TIFR, Bengaluru)*

Peering Into the Darkness – Imaging Black Hole Horizons
27 March 2025 ✦ *Speaker* — Feryal Özel *(Georgia Institute of Technology, USA)*
Science Gallery Bengaluru

What Happens at Shorter Distances?
14 February 2025 ✦ *Speaker —* Nathan Seiberg *(Institute for Advanced Study, Princeton, USA)*

The Many-Body Physics of Computation
15 January 2025 ✦ *Speaker —* Vedika Khemani *(Stanford University, USA)*

On Rational and Irrational Numbers, Strings and Harmony
6 December 2024 ✦ *Speaker —* Uri Onn *(Mathematical Sciences Institute, ANU),* Shubhadeep Chakraborty *(Guitar),* Michelle Simons *(Cello) and* Sayantan Mandal *(Piano)*

Einstein Lectures

Why are turbulent flows so fascinating?
27 February 2025 ✦ *Speaker —* Samriddhi Sankar Ray *(ICTS-TIFR, Bengaluru)*

Visveshwara Lectures

Quantum Astrophysics
18 January 2025 ✦ *Speaker —* Roger Blandford *(Stanford University, USA)*

KAAPI WITH KURIOSITY

Understanding Animal Societies
3 November 2024 ✦ *Speaker —* T.N.C. Vidya *(JNCASR, Bengaluru)* ✦ *Venue —* J. N. Planetarium, Bangalore

Three Puzzles from the First Billion Years
13 April 2025 ✦ *Speaker —* Girish Kulkarni *(TIFR, Mumbai)*

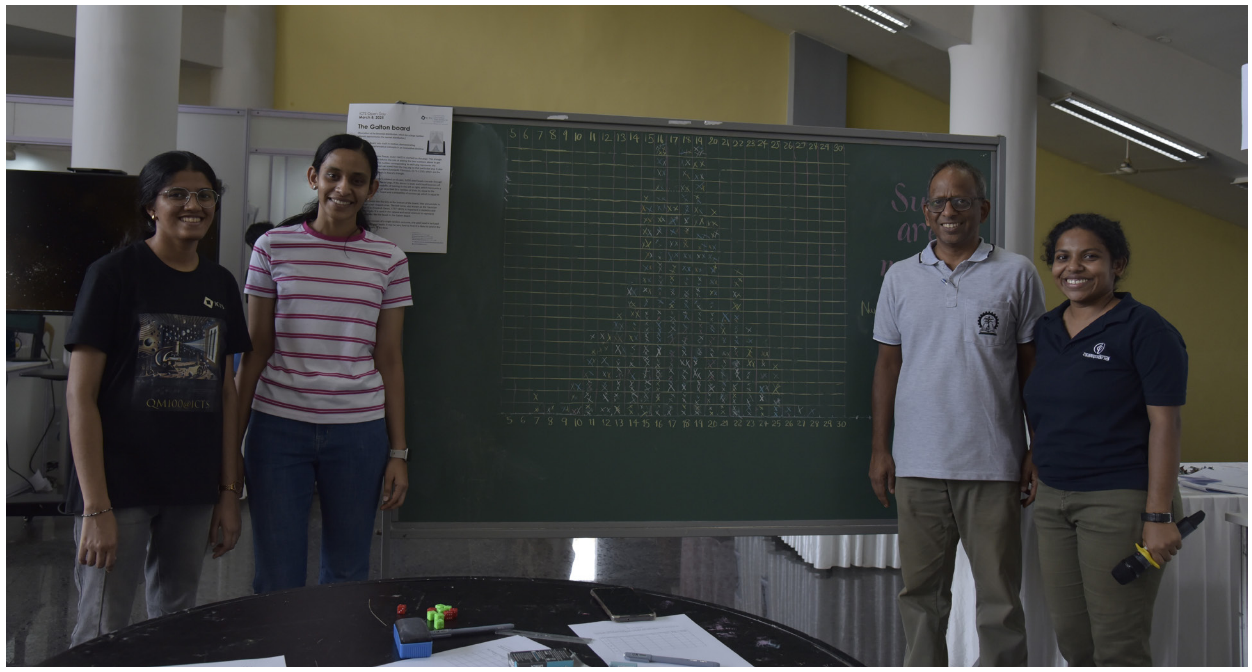
Curation as Misinformation
22 March 2025 ✦ *Speaker —* Cailin O'Connor *(University of California, Irvine, USA) and* James Owen Weatherall *(University of California, Irvine, USA)*

A History of Time
23 February 2025 ✦ *Speaker —* Spenta R. Wadia *(ICTS-TIFR, Bengaluru)*

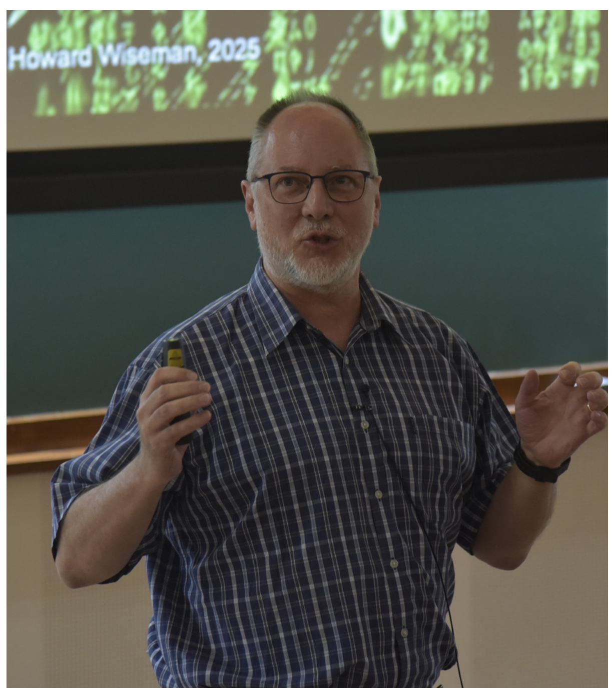
Quantum Mechanics: The Wild World of Atoms
25 January 2025 ✦ *Speaker —* Klaus Mølmer *(Niels Bohr Institute, Copenhagen, Denmark)*

Numbers: Are They Normal?
19 December 2024 ✦ *Speaker —* Malabika Pramanik *(University of British Columbia, Vancouver, Canada)*

Participants at the program Hundred Years of Quantum Mechanics at ICTS-TIFR, 13-17 January, 2025. Photo credit: AS Sumukh



ICTS Open Day festival, 8 March, 2025. Photo credit: PR Chandan



Howard Wiseman (Griffith University, Brisbane, Australia) delivers his ICTS Distinguished Lecture, 27 January, 2025. Photo credit: AS Sumukh

Deepak Dhar delivers the ICTS Foundation Day Lecture, 27 December, 2024. Photo credit: AS Sumukh

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