Face to Face

This section features conversations with personalities related to science, highlighting the factors and circumstances that guided them in making the career choice to be a scientist.

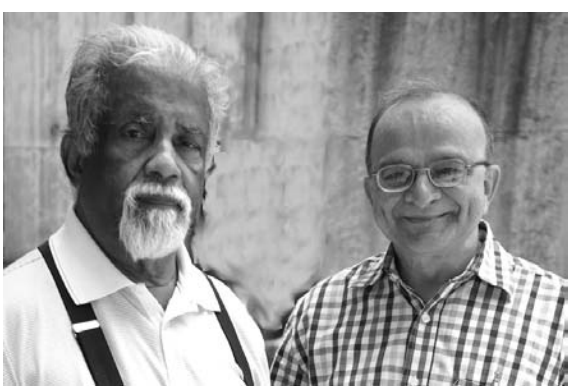
Symmetry and Mathematics

Pioneering Insights into the Structure of Physics

E C G Sudarshan talks to Urjit A Yajnik

Ennackal Chandy George Sudarshan is an outstanding Indian theoretical physicist. He had his early training in Madras Christian College and TIFR Bombay. His PhD thesis work in Rochester supervised by Marshak solved a pressing problem of particle physics – the precise nature of the so-called weak interaction (see article by G Rajasekaran in the January 2014 issue of *Resonance*). His brilliance was well recognized and he was offered a faculty position in the State University of New York at Rochester, where he developed the 'coherent state representation' for the quantum theory of light, which brings out a remarkable and unexpected mathematical parallel with classical wave optics and is a widely used tool today. He has contributed to many other areas of theoretical physics, both at Rochester and the University of Texas in Austin. As the founder of the Centre for Theoretical Studies at the Indian Institute of Science in Bengaluru, and the director of the Institute of Mathematical Sciences in Chennai, he has had a strong connection with the Indian physics community. In this interview with his former student, U A Yajnik, of the physics department at IIT Mumbai, he goes over the many momentous events of his long career with a light and informal touch.

Rajaram Nityananda
Editor



ECG Sudarshan (left) with U A Yajnik.

UAY: You are one of the rare human beings who glimpsed and explicated the structure of a new law of nature[1]. After Newton's gravitational law and the laws of electromagnetism, the weak nuclear force and the strong nuclear force are the only new ones to be discovered. Your law opened the path to the theory of the weak nuclear force.

Please say something about your family background, your school days.

ECG: I am one of three brothers. We are sort of an academic home as my mother was a school teacher and even when I was in college, I was afraid of my father finding fault with my English. Nobody in my family had a science background. When I was in middle school, I knew all the things that were taught in mathematics. There was no specific instruction, but mathematics never seemed to need any explaining. Sometimes, fellow students tried to test me by saying: the next mathematics class looks like a difficult topic, can you help us solve the problems? And I could solve. It was automatic. I did not understand how others found mathematics difficult.

By the time I was in high school I read my brother's physics textbook from college. I was tremendously impressed by the formula for the time period of a simple pendulum. There was length and there was 'g' and there was a square root, and then 2-pi which was an irrational number. But the book said the proof was beyond the scope of the book (laughs).

Similarly, in our book, there was the formula for 1 + 2 + 3 ... upto N and similarly for sum of squares. And I said I must find the formula for sum of cubes. And I tried various things, and did find the formula. Of course later I learnt this was quite trivial once you knew how to do it. But these were a few isolated incidents. These happened naturally. There was no competition with anyone. No one seemed interested in them.

UAY: You had the privilege to be just one generation following the one that discovered and formulated the principles of quantum mechanics. What was the atmosphere in physics when you set out to join the profession?

ECG: I was in Madras Christian College. I had some very good teachers, and their teaching provided inspiration to know more. Mr Thangaraj's optics course was inspiring. He liked to teach without referring to any notes. But then he carried little chits in his pocket which he would pull out at the correct moment (laughs), but he was really a very good teacher. Similarly, we had a very good teacher in mechanics. Optics was taught rather seriously in India due to

[1] **Fundamental forces of nature**: At current state of knowledge all the known forces can be seen to arise from four basic ones, Gravitation, Electromagnetism, Weak Nuclear and Strong Nuclear forces. This means one independent fundamental constant is required in the law governing each of these forces.

C V Raman's presence, but when we went abroad, it was considered out of fashion. [Comment for readers : This was to change soon with the arrival of quantum optics[2]].

UAY: You were at the Tata Institute of Fundamental Research as a fresh PhD student. Any recollections from the days at the Institute? Of the faculty there?

ECG: I was at TIFR for three years. [This was during 1952–55 when TIFR was located at Old Yacht Club building]. The food did not suit me at all. The rotis were horrible and there was no rice served in the canteen! Nothing that would suit a south indian palate. Later we discovered a south indian joint that would serve idlis. Among my contemporaries were Raja Ramanna, S S Jha, Suryanarayanan, K K Gupta.

I had been assigned to the experimental cosmic ray group that analysed emulsion tracks[3]. The work involved identifying emulsion tracks of cosmic rays with great precision. I had a great difficulty doing anything precise with my hands. But there was a fellow student called Biswas. His hand was steady as a rock. He could make the traveling microscope move at an absolutely steady pace and track the tracks accurately.

We were engaged in identifying these tracks and developing a model for how the concerned particle interacted with matter. A slower particle was easier to deal with as it made more frequent collisions and left sufficient markers. A faster particle was more difficult to track. We developed a model extrapolating the behaviour of slower particles statistically to that of the faster particles. The model turned out to be quite effective.

One summer I also started helping out with Dr Phadke's lab, whose group was designing an electron gun. He was very pleased with my participation, especially mathematical modeling and

[2] **Optics and quantum optics**: The laws governing light were known for long, in the context of reflection and passage through a variety of mediums. Whether light should be thought of as wave or particles remained an open question till Maxwell's theory showed light to be a derived effect of electricity and magnetism. He could also obtain a wave equation, the speed of which waves matched that of light. However the consensus that light is waves was soon to be broken by Einstein's 1905 observation that in many situations it also behaved like quanta, "packets of energy propagating undivided and without spreading in space". The comprehensive theory of light, Quantum Optics, which could account for both these characters could be developed based on S N Bose's contribution of 1924. A full description emerged only in 1963, and is ascribed independently to Glauber and Sudarshan.

[3] **Cosmic rays and emulsions tracks**: Just as the Earth receives light from stars and other heavenly bodies, the Earth also receives a continuous stream of charged and neutral particles of various types from outer space. They can be detected using radiation counters. Their origin and properties at present are reasonably well catalogued but not fully understood. In the early years of their discovery a standard strategy for their measurement was to expose a photographic plate to them. The layer on the photographic plate which undergoes a change and leaves behind dark tracks is called an emulsion, a pasty substance.

I remained a consultant to that group even later.

Some of this modeling experience was going to be of use later in theoretical work on stochastic evolution of the density matrix done in 1961, which has recently made its reappearance since late 1990's in the context of quantum computing. However the credit usually goes to the recent authors. Getting priority on it is difficult [laughs].

In my first year, Dirac[4] visited TIFR for six months and taught a course on quantum mechanics. I took notes for his course and would take the draft to him for approval. That allowed me to see him freely. To me, he became just like a friend and I could go and ask him all the doubts I had. Although he spoke little as is well known, he was very friendly to me.

UAY: Did Dirac ever say what inspired him to connect Heisenberg's first quantum proposal about non-commutativity of position and velocity to the Poisson bracket relations of classical mechanics between position and its canonical momentum?

ECG: According to him, the anti-symmetry property of commutation relations was shared with the same property of Poisson brackets. Likewise the Jacobi identity. Other then that, he mentioned that the analogy had been remarked also by E T Whittaker, although there seems to be no published record of the same.

UAY: You were scouted out by Robert Eugene Marshak, a distinguished nuclear physicist, and invited to join Rochester for pursuing a PhD. What are your recollections of that event?

ECG: Marshak visited TIFR during my second year. For leaving TIFR and applying abroad, we would need the approval of our advisor. When this point was explained to Marshak, he went over to my advisor and asked: Is there any difficulty with his leaving? And to someone like Marshak, he simply said there was no difficulty. But later, when I actually sought permission to leave, he said you would not be suited for theoretical research and therefore I cannot give you permission to go there. So the following year I changed my advisor and then sought permission again. This person was very liberal and granted the permission readily.

UAY: Upon completion of your PhD, you were given a fellowship to join Harvard University by the grand wizard of quantum field theory, Julian Schwinger. What was your interaction with him and your impressions and inspiration?

ECG: During one of the visits by Robert Oppenheimer, Marshak recommended me for a fellowship at the Institute for Advanced Study. He agreed but it was already a little late in the

[4] **Paul Dirac**: A pioneer of quantum theory, providing a coherent mathematical footing to the radically new laws of mechanics that were just then being propounded by Heisenberg and others.

term and he said the fellowship could be offered the following year. But when Marshak approached Schwinger, although I was late there too, he went out of his way to arrange a special fellowship for me, Harvard Corporate Fellow. There was a short interview. He was already aware of my **V**–**A** work[5]. The discussion was whether I knew any field theory beyond 'diagrams'[6]. Once it was clear that I understood field theory in a more general sense, I was hired [laughs].

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[5] **V–A** : To be read as '**V** minus **A**' refers to the completely unexpected structure of the weak nuclear force. **V** is vector. **A** is the axial vector which is one that does not change sign under mirror reflection. Magnetic field vector and angular momentum vector are some examples. The theory of nuclear interactions is organised in terms of the charges carried by the particles. Special relativity does not allow static interactions as a general concept. Hence interactions are between flows of charge, or currents. The known particles that participate in weak interaction are electrons and neutrinos. The charged current carried by them causes decay of the muon as well of the neutron. Enrico Fermi's first theory of weak interactions used only vector currents. With neutron decay occurring in many nuclei, the exact structure was unclear and it was common to use both vector and axial vector in arbitrary combination, like $a\mathbf{V} + b\mathbf{A}$, where a and b can be any numbers to be fitted from experiment. There is also a simpler possibility where no angular momentum is carried by the current, when it is called scalar or S and when twice as angular momentum as a vector is carried, when it is called tensor or T. Sudarshan and Marshak were the first to propose that the interaction is strictly of **V**–**A** type with S and T excluded and no other proportionality constants involved between **V** and **A**.

It was surprising because it meant that our world favoured a particular 'handedness'. Further surprise was that parity was not violated in some small measure, (eg., ratio b/a being much less than 1 would mean small amount of parity violation), but maximally, with $b/a = -1$. This is reflected in the fact that the neutrinos occur only as left handed particles, spinning always counter clockwise relative to direction of their motion. No right handed neutrino has been found in weak interactions. This rather asymmetric phenomenon seems ugly but actually it implied a new symmetry, namely the left and the right handed pieces of a spin half particle are independent. Further, it had an important implication, that the neutrino has to be massless, a fact borne out independently by other experiments. By late 1990's we knew that neutrinos have a tiny mass but when participating in the weak force only the left handed piece of it participates. At the time it was announced, the **V**–**A** law was a major shock, also because several experiments, due to inaccuracies, had contrary evidence. It therefore needed conviction and an understanding that it meant a new kind of symmetry to make the proposal.

[6] **Quantum field theory and diagrams**: Quantum mechanics suitable for tackling problems of atomic and molecular spectroscopy were developed first, during the late 1920's, in which the specific quanta being studied remain unchanged. However, the phenomena in which particles get created and destroyed, like absorption and emission of photons, decay of the neutron etc, require a broader framework of quantum mechanics. Quantum field theory provides the same, with a built in book keeping also of the Bosonic and Fermionic nature of the particles involved. Particles with integer spin are called bosons and half integral values of spin are called fermions. Bosons tend to preferentially get created in a state already occupied by other bosons of the same species, while fermions cannot be created in levels already occupied. These properties along with the laws of special relativity are correctly incorporated in quantum field theory.

Julian Schwinger and **Richard Feynman** were pioneers, developing and applying the new techniques of calculation in quantum field theory to explain minute but vital discrepancies in hydrogen spectrum and the magnetism of the electron, due to these effects. Feynman's methods relied on a pictorial representation with diagrams, suggesting creation and reabsorption of particles. Each diagram stood for a specific mathematical expression.

UAY: In your memoir titled ‘Mid-century adventures in physics’ written on the occasion of *the Fifty Years of Weak Interactions* conference held for the purpose at Fermilab in 1985, you have outlined in a detailed manner how you were the first to note the **V**–**A** or purely left-handed nature of the weak nuclear force. Your advisor seems to have been incredulous of the results since he did not allow you to present them at the conference happening in your own university.

ECG: There were three independent experiments conducted by established groups over a span of time that stood in the way of the new theory. It took some courage to claim these as wrong. One was Anderson’s experiment measuring the ratio of electron decay mode to muon decay mode of charged pions which reported too low a value. The second was angular correlations in ^{6}He carried out by Ruby at Colorado which found the presence of a tensor or ‘*T*’contribution. The third was ^{35}Ar experiment at Urbana carried out by Hermanfeld which seemed to show scalar terms ‘S’ in addition to vector term ‘**V**’. Thus, the idea that the interactions were purely of ‘**V**–**A**’ form was unacceptable at first.

UAY: You have also narrated in that article how the various other personalities involved failed to give you the due credit. Do you believe this was due to a cultural bias against you, or do you think this can happen to any young theorist, simply because he is unestablished?

ECG: No systemic reason.

UAY: As a young faculty member at Rochester you interacted with established optics experts such as Emil Wolf and L Mandel. You as a trio rapidly grasped the significance of the correlations observed in the Hanbury–Brown and Twiss[7] experiments, as being of quantum origin. How did you make the switch from the problems of elementary particles to this problem of optics?

ECG: From my MCC days in Madras, I was aware of the book by Born and Wolf. I had an excellent teacher there who inspired us into the subject of physical optics. When I arrived in Rochester I made an acquaintance with Wolf on my own. Mandel was actually a summer visitor. He was not a member of the faculty but he was very knowledgeable in techniques related to optics. He did go on to become known for his work and got a position at Rochester. Later on, his student Jeff Kimble spent his early faculty career at UT Austin as a faculty member before moving to CalTech.

[7] **Hanbury-Brown and Twiss effect**: This was a novel technique (1956) in astronomy, using two detectors separated by a few meters, that allowed determination of the angular size of a distant star. The effect had classical, wave explanation in many cases, but full understanding was possible only by invoking the quantum properties of light.

UAY: Glauber's startling discovery that the large correlations in the Hanbury–Brown and Twiss experiments were entirely of quantum nature followed after the three author paper of Mandel, Sudarshan and Wolf. What inspired you to identify the final definitive form of the density matrix for the photons? Did you have any other formalism as a guide or inspiration at that point?

ECG: We had a paper but our considerations were primarily classical and we had missed the mark. Later that year, Wolf went to a conference in Paris. When he came back he appeared dejected. I asked him what it was, and he said Glauber had got definitive results, but that he was unable to follow everything because it involved quantum mechanics. He said that at his age he could not start learning quantum mechanics and he despaired of ever catching up with what Glauber had achieved. I reassured him that the new results could be cast entirely in a language he could understand, without having to learn anything new.

That evening I got to work and produced the answer in the form of a density matrix. It did require outlandish things such as derivatives of the delta function, unusual in classical treatments. The next day, I explained the whole thing to him. He said you must write it up as a paper. I said I would do it in the evening. He said, no you must do it now. I skipped lunch and wrote out the paper. His secretary typed it out. We proof read the paper and he sent it out by priority mail forthwith. Only then, I could go for lunch.

UAY: This result of yours, along with Glauber's result came to be called the Glauber–Sudarshan P-representation. The pathbreaking conclusion of your paper, loosely paraphrased is that 'the density matrix obtained was a complete description of all the states of the free electromagnetic field, including for the usual classical electromagnetic waves'. The implication was that the usual description taught as 'classical' theory to all engineers and physicists, was indeed fully quantum mechanical, even though Planck constant, which is a hallmark of quantum mechanical phenomena did not make its appearance for a special reason. Is this correct?

ECG : Yes.

UAY : What led to your decision to settle in the USA?

ECG : Well, as I said, my advisor in India had told me, " you will not make it", while when I reached Rochester, they asked, "where were you all this time" [laughs]. But actually it was just sort of inertia. [One thing just led to another]. I had expected PhD to last five years. Instead, I finished in two years. And then I had this job with Schwinger. When Marshak asked me at one point, I said I will go back to India after the postdoc at Harvard. But he offered me a job. When

Bhabha told Marshak that he was considering offering me a job, Marshak said but he already has a job.

UAY: So Bhabha also offered you a job?

ECG: Yes, he called me to Washington to meet him. Gell–Mann had then recently visited TIFR and given lectures on SU(3)[8]. Bhabha was aware of **V**–**A** and my role in it. But Marshak told him that I was going to Rochester.

That first year I joined Rochester was the most memorable one. Marshak was out of the country. This meant that all his students would be handled by the other senior professor in the department, Gabor. But Gabor had some personal problems and was out of action. Thus, I had the responsibility of ten graduate students in addition to teaching. Of course, I love to teach. But these were rather exceptional students. There were Tom Jordan, Douglas Curry and Korkut Bardakci. I lived in a bachelor apartment near the student accommodations and I had told the students they were free to approach me any time. Thus, I was always on the phone if I was not actually with them.

Jordan was good with mathematics, he would work things out and we would write papers, while Curry, although good at physics, was always arguing. At that point I was studying Dirac's proposal for how to formulate relativistic theories of quantum mechanics. He had said that you must find the relevant representation of the Lorentz group and that was sufficient. Curry said, that is not enough, you must have world lines. Now having world lines was all very good but how to implement this idea in a quantum system was not clear. He bugged me for a whole year. Eventually, Jordan, Curry and I wrote a paper on manifest covariance versus relativistic invariance[9]. He was right. Manifest covariance of the world line is not the same as Lorentz invariance. That sounds ridiculous in one way of looking at it. But it was true in another way of looking.

[8] **SU(3)** : Short form used to refer to a particular algebra, one that encodes the mathematics of rotations in an abstract sense. This abstract kind of rotation is a symmetry of the nuclear forces between hadrons. Hadrons is a generic term for a class of particles like pi-mesons, K-mesons, protons, and similar heavy particles which could be created and studied systematically at the cyclotron accelerators. Capability to produce and study such particles marked the beginning of the subject of elementary particle physics. For those familiar with some mathematics, SU(3) stands for the group formed by unitary matrices of size 3×3 with determinant unity.

[9] **Manifest covariance and relativistic invariance**: Relativistic Invariance refers to a property of the mathematical description which leads to answers which respect the principle of special relativity. Relativistic invariance is the same as Lorentz invariance. Manifest covariance is a more restrictive meaning, where not only does the mathematical framework respects the principle, but all mathematical expressions directly, at a glance, convey that they respect the principle. The specific issue referred here is more subtle and beyond the scope of explanation here.

Thus, it was a very intense period for me handling ten students. Every time I turned I thought of something new. And there was always someone at hand who would argue that you were wrong or in what way you were right.

That was much before Mukunda[10]. By the time Mukunda joined, Sudarshan was already an established establishment. Mukunda had done Mathematics from Delhi University and he was phenomenal. I was almost afraid to talk to him. Any time you talked, he told you you were right or you were wrong. The year he arrived, I was teaching classical mechanics. I did not like the way it was presented in usual textbooks, in a mechanical way. So I began to do it differently. Mukunda wrote up the notes. And after I saw the notes, I thought I must have been wise, because there are so many good things.

Here, I have to admit I could never get the signs of certain commutation relations[11] correct. Rigid body rotation is remarkable because it is a non-linear problem[12] that is completely solvable in terms of one integral. But the commutation relations for body centered and face centred systems are different. And I could never get the signs right. Mukunda sorted that out. When I looked at it, I said where is the problem? There was no problem. Indeed, any discussion with Mukunda became a substantial discussion.

UAY: Please allow me to make a preamble for my next question: the dissatisfaction with quantum principles is somehow raised much more virulently than that with the famous lacuna of 'instantaneous velocity'[13] in the Newtonian paradigm. People who consider classical

[10] **N Mukunda and Sudarshan** collaborated in Rochester, and later in Bengaluru, on classical dynamics (on which they wrote a very well known book) and optics. Mukunda is also the founding editor of *Resonance*.

[11] **Commutation relations**: Certain mathematical relations, specially occurring in quantum mechanics.

[12] **Non-linear problems**: These are usually difficult problems where no general techniques may be applicable and for each type of problem special techniques have to be devised.

[13] **Instantaneous velocity**: Newton assumes as part of his mathematical philosophy, that a material particle can be ascribed a speed also while it is at a specific point in space. This is counter intuitive since a particle *at* a point cannot be 'moving', and if not moving, cannot be ascribed any velocity. Newton therefore carefully defined the concept as a limiting value of measurements made at different times, while the time difference is progressively allowed to be indefinitely small. However, just as the mathematical concept of a point is an abstraction, so is the limit of indefinitely short time lapse. From the empirical point of view of science, one must carry out the experiment in practice to see if space can be pin pointed as suggested by the concept of a point, likewise whether intervals of time can be made indefinitely short. Our modern understanding is that when we begin to do this, we encounter the quantum domain where actually Newtonian rules break down. While many people find the new laws of quantum mechanics puzzling, they do not object to the Newtonian idealisation as not empirically tested.

The concept of motion has long been a source of puzzles, some of which were articulated by Greek philosopher Zeno. It is also discussed extensively in Indian philosophical systems such as Nyaya and Vaiseshika and the Madhyamika school of Buddhism.

mechanics a more satisfactory description of nature readily assume that the limits needed by Newton exist objectively in nature.

ECG: The problem with quantum mechanics is that it is not classical mechanics [laughs].

UAY: The quantum level reveals newer formulation of Zeno's logical puzzlement which yourself and Baidyanath Misra elucidated in 1977. Can you please elaborate on it?

ECG: It started with a comment by Baidyanath Mishra who commented that the theory of continuous semigroups[14] says that something cannot start with a constant rate. And he went on to remark that therefore the decay law cannot be exponential. When we completed the work, people took note. We had proposed that repeated measurement of an unstable excited state will postpone its decay. This follows from the usual interpretation of quantum mechanics. Roughly speaking, the process of observing it in that state makes the probability of it being found again in that state unity, thus providing its durability. I had a Chinese student to whom I gave a problem related to this. And she had a daughter. When she learnt what Zeno effect was, she said, "Mom, you keep checking if I am growing up. That is why I am not growing up". [Laughs].

However when the effect began to be probed, they found the 'anti-Zeno effect'. They found the rate increasing instead of decreasing. This had simply to do with the fact that the intervals over which the observations were carried out were not as short as required by our theory. Later, my colleague Mark Raisen at the University of Texas at Austin found, in fact, an opposite observation, that under observations over extremely small time steps, the state decayed faster. This required us to revisit our original reasoning. There are theorems to the effect that with usual assumptions of quantum evolution, the decay rate has to be an analytic function of time, and also that it must go to zero. The exponential decay law[15] is not an analytic function in time at infinity, hence contrary to popular belief, it is wrong. And these arcane mathematical things come and hit you when you least expect them [laughs]. As a result the rate can also not be strictly constant at initial instants of time. Thus, a journey that had started with property of continuous semigroups, [laughs] which nobody would have understood, resulted in some interesting insights.

UAY: The interpretation of quantum mechanics has left behind a nagging sense of incomplete-

[14]**The theory of continuous semi-groups**: This refers to an unusual kind of algebra and is not intended to elucidate. It is mentioned here more as something abstruse and which was a false start.

[15]**Exponential decay law**: The law governing the time dependence of how excited an system loses energy to relax to a lower energy state. The word exponential refers to its specific mathematical form, usually covered in high school.

ness that is articulated by the EPR paradox yet stubbornly proved internally consistent by Bell's inequality[16]. Much intellectual effort and critical experimentation continue to improve our understanding on this front. Can you say something about a formalism you have developed that potentially addresses this?

ECG : While analysing particle tracks in emulsions as a student at TIFR, we had to develop a model for evolution of a trajectory in presence of multiple scattering plus noise. Later, when I started working with Mandel and Wolf, well, Mandel was an experimentalist but he was also good at these theoretical tools. There was a method for evolution of 2 by 2 matrices of the polarisation states of photons called Jones calculus. I found out that the formalism could also be extended to the density matrix[17] in quantum mechanics which nobody seemed to have done. The method I developed applied to *n* by *n* matrices. It became a big hit.

Then [some years later], I came across somebody who was very mathematically oriented; Gorini who actually came to work with me as a research associate. He was interested in other topics but I set him on the right path [laughs] and he got working on this topic. He soon discovered that there was formalism developed by Kossakowski, who had written down what may be considered the most general kind of evolution equation, including for systems that are not Hamiltonian[18]. Now Kossakowski was so learned that he talked in terms of functionals and ... [laughs]. It was impossible to quite understand what he said. He had published this paper in Poland and sent its copies to various people. The equation he had developed was popularly known as Lindblad equation. Lindblad in Sweden had read Kossakowski's paper and written a very lucid paper. We persuaded Kossakowski to join us in developing the paper we were writing.

[16]**EPR paradox and Bell's inequality**: Einstein–Podolsky–Rosen paradox refers to a conceptual issue with quantum mechanics raised by the authors after whom it is named. Bell's inequality is a condition that if satisfied in quantum mechanics experiments, would make quantum mechanics compatible with standard intuition regarding objective reality. In practice Bell's inequalities are violated by all experiments in the quantum domain, showing that our usual intuition is not adequate to understand these effects heuristically. While majority of experts accept this as a limitation of human perception and cognition, many philosophers feel that it indicates an inadequacy of the quantum mechanical framework.

[17]**Density matrix**: A mathematical framework for quantum mechanics (and quantum field theory), which is equivalent to but different from the wave function framework. It is advantageous in treating some class of problems.

[18]**Systems that are not Hamiltonian**: The usual mechanical systems studied obey a framework referred to be the name of its inventor, Hamilton. Evolution refers to evolution in time. The framework being referred to therefore is being highlighted for being able to handle time evolution that has unknown and unpredictable disturbances in it, but also those that which would not be amenable to standard methods even if the unpredictable effects were absent.

The objects of interest it turns out, are maps[19] that convert one density matrix into another. And while the density matrix is always positive, the maps that do the conversion need not be. We developed suitable characterisation[20] of the general form of such maps which is also sometimes called the 'operator sum' method. Also, this business of matrices, applies not only to polarised light and lenses and such [laughs], but to any finite size matrices such as those used for many quantum systems. These manipulations with these matrices, it turns out, are exactly what is the process of quantum computing. At first it is difficult to see the connection from classical optics to such processes but once you understand the problem you can see that it is really the same mathematical problem. Likewise, the same equation has been revisited in 1990's in the context of black holes [information paradox].

UAY: You have remained a citizen of India through out your long professional career in the USA. You also have received Padmabhushan from India. You founded the Centre for Theoretical Studies at IISc Bangalore and later became Director of the Institute of Mathematical Sciences, Chennai, giving it its modern form. What are your recollections of these efforts? [Note to readers: Institute of Mathematical Sciences was at one time abbreviated as Matscience, while the current standard abbreviation is IMSc]

ECG: When I took over Matscience, its budget was 3 crores. By the time I handed over five years later, it was 30 crore. A lot went into building infrastructure, particularly the library which was notorious for its rats, and following them, snakes. Further, the salaries of the academic staff had remained extremely low. Asking for more money for science in those days was like Oliver Twist asking for more soup. There was much discussion about parity of the academic positions at Matscience versus other institutes of the DAE. Finally, the DAE agreed and Matscience faculty received substantial raises.

I was also offered IISc directorship at one point but those discussions did not come to a head. Then, we set up the Center for Theoretical studies in IISc. Its mandate was carrying out interdisciplinary research applying mathematics to both basic and applied sciences.

UAY: What is your message for students opting for research in pure physics today?

ECG: When I was a research student, it was considered an opportunity to be able to work on something. Nobody had to ask you to do 'this'. They suggested that may be you can look at this.

[19] **Maps**: The mathematical concept referring to the process of associating elements of one set to those of another – in this context, this refers to mapping the state of the system at one time to that at another time.

[20] **Characterisation**: Arriving at principles that put the several different cases in a systematic perspective. In simple words, solution of the problem.

And then you did it. If you did not know enough you read up about it. Or you asked various other people. Somehow, this culture of doing things out of one's own curiosity and by one's own efforts or by discussion with other people is gone from students. Our education has gone down. At Madras [MCC], I learnt more than people now learn in the course of their PhD.

It is not that they are not sophisticated. But somehow the idea that physics is a connected subject has gone. If you are a physicist, you must know about melting of ice. You know, melting of ice is a very complicated subject because there are so many allotropic modifications of ice. The thing is that these things are connected, very closely connected. You should realise that what you know about quantum mechanics is related to why water behaves the way it does. But nobody thinks like that. They say, ah, water is water.

Once you develop this habit, nothing is outside your scope. Raman used to say, what is the basis of colour? Butterflies are blue and they go to hibiscus flower which are also a particular shade of blue. And he cultivated different varieties of this blue flower to see if the butterflies will go to all of them. He said they must know something about spectroscopy if they are able to find out [laughs]. Raman also had a theory about vibrating strings. And it may even seem funny to some that such a great man should worry about musical instruments. But he elevated these investigations to inspired inquiry. The same sense of inspired inquiry needs to be brought into the honours class.

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