E. C. G. Sudarshan (1931–2018)

On 13 May 2018 the world lost a physicist of deep insight and vision, one of those few who glimpse and formulate a new law of nature. Ennackal Chandy George Sudarshan, born 16 September 1931, was a pioneer of several uncharted territories in physics. Some of them were very timely in the 1950s and 1960s and some others were far ahead of their time, and are beginning to be appreciated only now. One work that became sensational and enchants the common man and had made it to the *New York Times* is the theory of tachyons, particles faster than the speed of light. The one that is thriving in the emerging mathematics of quantum information is the Stochastic Dynamics of quantum systems. The one that brings out a fascinating reconfirmation of the uncanny nature of Quantum Measurement is the formulation of Quantum Zeno's paradox. The one that launched him into limelight, at the young age of 26, having seen the universal chiral character of the Weak nuclear force, is the V–A theory. And the one that raised so much hope of Indian science for receiving the highest recognition in fundamental science is the definitive characterization, the Diagonal Representation for quantum state of light.

If his public image is large and appropriately makes the rounds of the national and particularly the Malayalam press, it may justifiably be called smaller than it should really be. This is because very few professional physicists have actually studied the variety of his contributions, and understood their import; hence for the common public the origin of his greatness is mostly a very distant glimpse. Those who were exposed to any one of his major contributions became his life-long admirers, and very few could actually interact with him on the full breadth of his opus. A person of great energy, enthusiasm and ready wit, he impressed everyone who came close to him. I will outline here a few of his best known contributions which should put his work into perspective. This will be interspersed with some of his life's vita and some reminiscences archived in proceedings of professional meetings and some conveyed in personal interaction with the author.

'V minus A', or, chirality as the foundation of weak interactions

By far the most far-reaching scientific contribution of Sudarshan was made in the course of his Ph D at the University of Rochester, under the supervision of Robert Eugene Marshak. Let us briefly recall the state of the theory of nuclear interactions. The theory of beta decay with local interaction among four spinors was proposed by Fermi in 1934 apparently in analogy with electromagnetism. However, considerations of Lorentz invariance permitted five such possible interactions, S, V, T, A and P familiar to students of relativistic quantum mechanics. In fact, a combination of T and A was advocated by George Gamow and

Edward Teller in 1936 to account for spin effects in nuclear interactions in the non-relativistic limit. No unique version of the Hamiltonian possessing theoretical simplicity was forthcoming, and the above developments made it imperative to consider all the kinds of terms. By 1956, in response to other developments in hadronic physics, Lee and Yang were led to make the bold proposal that parity (i.e. the symmetry under space reversal or mirror reflection) was not conserved in those hadronic processes, and in weak interactions in general. This proposal was quickly confirmed by an ingenious experiment in 1957 by C. S. Wu and team with ^{60}Co in which the beta particles were found to be preferentially emitted in the direction opposite to the nuclear spin. This experiment may justifiably be considered one of the classics of modern physics.

These developments should have been a spur for the search for a universal form of the weak interactions. However, the experimental status did not support such a quest. A thorough analysis by Sudarshan as a graduate student led him to realize that several of the experiments reported by well-established groups had to be erroneous for a universal law to be true. As the experiments came from widely different experimental settings and different laboratories, presuming them to be wrong required strong conviction.

However, convinced by their reasoning, Sudarshan and Marshak asserted at the Padua-Venice conference in 1957, 'While it is clear that a mixture of vector and axial vector is the only universal four-fermion interaction which is possible and possesses many elegant features, it appears that one published and several unpublished experiments cannot be reconciled with this hypothesis. These experiments are: (a) the electron neutrino angular correlation in ^{6}He...; (b) the sign of the electron polarization from meson decay...; (c) the frequency of the electron mode in pion decay; and (d) the asymmetry from polarized neutron decay ... If any of the above experiments stands, it will be necessary to abandon the hypothesis of a universal V–A four-fermion interaction.' This assertion led to all the four experiments being carried out again, and the new results were found to accord exactly with the V–A structure proposed by Sudarshan and Marshak.

A fundamental force of nature ought to have a universal structure; conversely, one would not consider a law to be 'fundamental' if it did not possess such a universal structure. Importantly, we expect the universality to be associated with a conservation law or a symmetry principle, such as flux conservation associated with the $1/r^2$ form of gravitation and electrostatics. Sudarshan and Marshak indeed also emphasized the corresponding new principle, that of Chirality Invariance. In their 1957 paper they said, 'The universal Fermi interaction, while not preserving parity, preserves chirality and the maximal violation of parity is brought about by the requirement of chirality invariance. This is an elegant formal principle, which can now replace the Lee–Yang requirement of a two-component neutrino field coupling.'

The work reported at the Padua–Venice conference remained unpublished. Sudarshan recalls that even before Padua–Venice, he already had the results by the time a major conference was hosted by his own group at Rochester[1]. However Marshak hesitated in allowing him to make a presentation of his new results. Over a coffee session during this conference, both of them shared with Gell-Mann the key idea of V–A structure of weak interactions. Soon after, the same theory was published by Feynman and Gell-Mann, with no mention of the interaction that had occurred during the Rochester Conference. And the V–A theory began to be popularly associated with these two names. Many years later at another workshop where Feynman was lecturing, he acknowledged personally to Sudarshan that he had come to know that Sudarshan was the first to have understood the validity of the V–A structure. Feynman seems to have also acknowledged it more publicly in other fora, however Marshak and Sudarshan had lost the priority over that discovery.

The universal V–A theory later became the indispensable ingredient of all the developments in Elementary Particle Physics. Within a decade of its discovery, the definitive formulation of electroweak theory emerged in 1967. Its proponents, Sheldon Glashow, Steven Weinberg and Abdus Salam, needed to assign unequal weak charges to the right and the left chiral components of the known fermions, with the right-handed neutrino absent altogether. The same principle also correctly embraced both, the hadronic and leptonic weak interactions of the quarks. This work unifying weak and electromagnetic interactions was recognized by the Nobel Prize of 1979.

Chiral invariance as a general principle and its breakdown due to strong dynamics became the first foray into investigations of broken symmetry in the hands of Yoichiro Nambu in 1960. The modern understanding of the masses of light hadrons such as mesons is also based on this general principle. As further developments continued, it was soon recognized that chiral fermions were the key building blocks of the Grand Unification proposals. The principle of chirality assured that all the fermion masses emerged from the principle of spontaneous symmetry breaking. At present it is an open question whether nature is indeed symmetric between left- and right-handed fermionic matter at very high energy scales. The V–A structure at low energies could be accompanied by an equally elegant V+A structure, albeit hidden by spontaneous breaking of symmetry in the specific vacuum we reside in. These exciting possibilities are formulated on the pillars of the chiral V–A structure of weak interactions.

Initiation into research physics

Sudarshan began his advanced work in physics as a fresh Ph D student at the Tata Institute of Fundamental Research (TIFR), Mumbai. His reminiscences of those early days do not set him apart much from most of the clever graduate students we see in physics. He complains about non-availability of idlis in the Colaba area, having arrived directly from deep South to Mumbai of 1950s. He was assigned to work on experimental physics. From his narration it is clear that he enjoyed his experimental work and also innovated with it, and was even appreciated for his work carried out for one of the groups. But he admits that there were students better at experimental work than him[2].

During this period P. A. M. Dirac visited TIFR and gave a series of lectures. Sudarshan recounts his good fortune in being the official note taker on this occasion and the opportunity it provided him to talk freely to Dirac. This is all the more significant as Dirac is famous for his reticence and monosyllabic replies to queries. But we may note that among the galaxy of great pioneers of quantum theory, Dirac alone seems to have remained unsurprised by the new mechanics and its rules. Dirac was the first to bring out the formal structure and elegance of quantum dynamics through the correspondence of its algebra of operators with the algebra of Poisson Brackets of Classical Mechanics. He was also the pioneer in recognizing the relevance of Hamilton's Principal Function in quantum dynamics, a truly elegant formulation that later came to be developed as the Path Integral quantization. This work emphasized the formal elegance of contact transformations in dynamics. As we shall see, these themes were to remain with George who explored and enhanced them with great depth and passion throughout his life.

After two years at TIFR, Robert Marshak, an acclaimed nuclear physicist, came to visit. And he spotted the talent in Sudarshan. He offered to take him as a

E. C. G. Sudarshan – Significant dates, some honours

Born 16 September 1931 in Pallam, Kottayam, Kerala
Student of Intermediate – CMS College, Kottayam, 1946–1948
BSc (Hons) Physics – Madras Christian College, Chennai, 1948–1951
MA – University of Madras, Chennai, 1952
Research student at TIFR, Mumbai, 1952–1955
PhD student of R. E. Marshak, University of Rochester, NY, 1955–1958
Research Fellow with J. Schwinger, Harvard University, Cambridge, MA, 1957–1959
Assistant Professor, University of Rochester, NY, 1959–1961
Associate Professor, University of Rochester, NY, 1961–1963
Professor, Syracuse University, Syracuse, NY, 1964–1969
Professor, University of Texas at Austin, Austin, Texas, 1969 onwards
Director, Centre for Theoretical Studies, IISc, Bengaluru, 1972–1983
Director, The Institute of Mathematical Sciences, Chennai, 1983–1988
Padma Bhushan – 1976, Padma Vibhushan – 2007
Fellow of the Indian Academy of Sciences (FASc) – 1963; Fellow of the Indian National Science Academy (FNA) – 1972
First TWAS Physics Prize – 1985; Dirac Medal of ICTP, Trieste (Italy) – 2010
First Majorana Prize of *Electronic Journal of Theoretical Physics* – 2006
Died 13 May 2018 in Austin, Texas, USA

student at Rochester, however that was predicated on Sudarshan being released by his current research director. As it happened this latter release was not forthcoming. The reason cited was that 'he will have difficulty doing theoretical work'. And one more year passed. At that point Sudarshan left on his own and joined Rochester. He jokingly remembered, here I was being declared unfit to do theory, and when I reached there, they said where have you been all the while?

Quantum theory

It is truly unfortunate that the new science of quantum mechanics continues to be regarded as mysterious, uncanny, etc., and further proscribed from being understood by assertions such as 'if someone claims to understand quantum mechanics, they are mistaken'. Indeed the simple fact that classical mechanics itself, based on Newton's conception of the continuum, was accepted without verification is completely overlooked when making these assertions. For no one actually took a stop watch, as Galileo would surely have done, and allowed time intervals to go to the mathematically correct limit zero, nor does one ever measure lengths till they shrink to the idealized zero. Indeed when such exercises were eventually taken up, we discovered, *inter alia*, as if by accident, a new Mechanics. But we forget that the calculus limits were a figment of our imagination, and the reality regarding miniscule scales and permissible values of energy were being revealed only then, for the first time, post the year 1900.

It was a fortuitous happenstance that Sudarshan with his calibre had as a mentor, even for a brief period, a person such as Dirac whose understanding of quantum mechanics was uncluttered by prejudice and who emphasized the principle of linear superposition as the true foundation of the new mechanics.

The development of quantum electrodynamics stretched the framework of known mathematics to its extreme limits. The delta function that Dirac introduced and utilized with great facility took several decades for its acceptance in mathematics. We now understand the mathematics of quantum theory as a rather raw extension of functional analysis, and its most general possibilities are probably still open. It was in this unfathomed and scarcely charted area that Sudarshan delved and continued to work on a variety of its aspects with great passion over several decades.

The calculability of atomic binding energies had raised great expectations from Quantum Theory. However, in the relativistic arena, much of that intuition became unviable. The question of computing relativistic bound states, the question of unstable states, the concept of spin, the questions of correct quantization conditions for particles of integer and half integer spins, all of these had, if at all, difficult resolutions. All of these themes occur in Sudarshan's life long work, done singly or with collaborators and receive an elegant treatment always ending with a characterization or classification of the issues. His main tools consist of generalizations to continuous field variables of the mathematical principles of Quantum Mechanics as laid out by Dirac, von Neumann and others, and analysis in terms of symmetry groups pioneered by Sophus Lie, and their representations in a generalized sense.

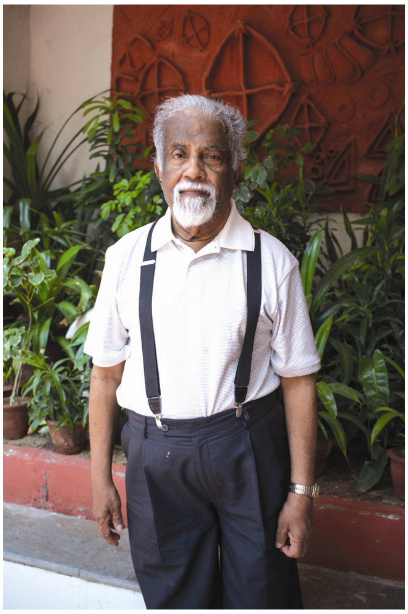

Photo credit: Avani Tanya, August 2014

In the case of special relativity, a fundamental 'no-go theorem' was observed and elaborated by D.G. Currie, T.F. Jordan, and later by G. Marmo and N. Mukunda along with Sudarshan in several publications, which states the impossibility of constructing an interaction potential in the Lagrangian sense. On the other hand he worked on the theme with several collaborators, including V. K. Deshpande and O. M. Bilaniuk that tachyons, particles faster than light, remain a marginally permitted possibility. His research also presents the representation theory of tachyons, according to which such particles should either be Lorentz scalars, or be a member of an infinite tower of states of non-zero spin. This classification worked out in the 1960s could very easily rule out the tachyonic neutrinos reported in 2009. Either what was observed had to be a scalar, or it would imply an infinite number of species of tachyonic neutrinos. He lectured on this theme during that time, including at TIFR.

Sudarshan worked to extend the framework of Hilbert space as enhanced by Dirac and other pioneers ever further to encompass possible newer quantum systems. These included the well-known problem of the 1940s, namely the indefinite metric quantization needed for Quantum Electrodynamics, but in some cases his work also sought to establish the possibility of generalized quantum systems hitherto not encountered but permitted in principle. He sought a formulation that permitted the existence of unstable particles and the most general rules for their decay, spectra consistent with the S-matrix that admit a bound state within the continuum of asymptotic states, quanta that obey para-statistics and so on. Some of these developments resonate with later formulations such as anyons in 2-space dimensional systems.

One of the outcomes of these studies was Zeno's paradox in quantum mechanics, a formulation that has received confirmation through difficult experiments and is yet being investigated. This work done with B. Misra shows that 'an observed quantum kettle indeed cannot boil'. More correctly, the rules of the behaviour of quantum systems in interaction with an observing apparatus suggest that an unstable state may not decay if observed with sufficient frequency.

The final word on the nature of light

Among the explorations of quantum systems and their representation is the classic work on diagonal representation for the states of photons in 1963. This work utilizes an over-complete basis such as provided by coherent states and recasts the complete quantum description of possible states of photons in a language that replicates classical treatment, but generalizes it to quantum operators. This 'quantum theory of partial coherence', encompassing in a comprehensive formulation, both the familiar classical description and exotic quantum states continued to engage him throughout his life in various contexts with several collaborators. All of the possibilities formulated and predicted by this method have not yet been observed. It is this diagonal representation or the theory of partial coherence that came to be known as the P-representation of Glauber and Sudarshan. Glauber received the Nobel Prize for this work in 2005.

Recalling the antecedents of this 1963 *Physical Review Letters* paper of mere 2-page length, Sudarshan has said that the Hanbury Brown and Twiss experiments involving intensity correlations were throwing up new challenges to optics. It was suspected that there were thermal fluctuations at work, but also possibly some quantum effects. Sudarshan was then at Rochester as a young Associate Professor. Although his subject had been Elementary Particles and Quantum Field Theory, he had a keen interest in optics. He ascribes this interest to a masterly exposition he got to optics at Madras Christian College during his BSc days from a very inspiring teacher. As a part of those studies Sudarshan had read the famous optics text of Born and Wolf. And this Emil Wolf was a senior faculty member at Rochester. Wolf returned from one of the conferences in Europe and he seemed dejected as he did not understand the new developments in his own forte Optics because Glauber had an explanation for the new phenomena in terms of quantum mechanics and he lamented that it was too late in his life to learn quantum theory. Sudarshan then went home and recast the quantum description of photons entirely in a language understandable to a classical physicist. In doing so he had to again stretch some of the rules about positivity, differentiability, etc., but the next day he could produce a mathematical formulation that was satisfactory to Wolf. Wolf then did not allow Sudarshan to go for lunch and insisted that he write out his work as a paper. It was immediately typed out by the secretary, they both proof-read it and only when the paper was put in express mail, was he allowed to go.

This urgency proved to be important as it established Sudarshan's (and the Rochester group's) priority in the work, a matter that was to become important later. This was the formulation that was alternative to Glauber's and as Sudarshan and collaborators elucidated over the next several years, comprehensive enough to encompass both classical and quantum states of light exhaustively. In fact, it proves that the presumed classical states of light are in fact quantum although we do not see any tell-tale presence of the Planck constant h in them. What this means in turn is that the superposition principle taught to undergraduate students of electromagnetism reappears at the level of single photon states within the Hilbert space used in quantum electrodynamics. The general Superposition Principle in quantum mechanics is however much deeper as it applies to all quantum systems including those made up of particles.

This particular elaboration was not included in the works of Glauber. And this exhaustive description due to Sudarshan has not been ascribed due importance or received due attention even in our textbooks. We may note that the fundamental property of photons, which by a misnomer is called 'indistinguishability', more properly the correct rules for indexing the independent states of photons, was first uncovered by S. N. Bose in his 1924 work. While Einstein had correctly understood quantization as an intrinsic property of light, he had never succeeded in deriving the Planck distribution based on this hypothesis[3]. It was S. N. Bose who provided the proof. Several decades later in 1963 Sudarshan, building upon the Bose statistics obeyed by photons, provided the most comprehensive description of light. This can be seen to have put a final end to the lasting controversy on the nature of light, that began with Newton, Huygens and Young. In the light of Sudarshan's work, the answer to the age-old question of the nature of light is profound and bewildering. Light can manifest, depending on circumstances, both as classical waves and as photons without there being contradiction between the two descriptions. And both the manifestations are founded on one unifying principle, viz. that photons obey Bose Statistics, more correctly speaking, the Bose enumeration of states. The two major foundational theoretical contributions of Indian scientists in resolving the age-old conceptual problem have not received their due credit.

Mentors and proteges

Soon after Sudarshan finished his Ph D at Rochester, his fame was spreading. Oppenheimer was ready to make him an offer in the next cycle of recruitments. But Schwinger went ahead and managed an unusual source of funding to bring young Sudarshan to the Harvard Society of Fellows. Julian Schwinger, Gunnar Källén, E. C. G. Stueckelberg (whom he also remembered light-heartedly for having shared his initials), are all reminisced by Sudarshan as people who impressed him and inspired him. Those were the heady days of innovating with quantized fields and enhancing the scope of the space of functions and operators on them.

After his Harvard fellowship, Sudarshan had planned to go to back to India. But Marshak pre-empted this by offering a regular positon at Rochester. Homi Bhabha had also sought to meet Sudarshan, and invited him for a meeting in Washington DC. But Marshak apparently told him 'but he already has a job'.

As it happened, in 1959 when he joined Rochester as a young Assistant Professor, the other senior professors in the group were on a sabbatical or otherwise unavailable. As such he had almost ten students and postdocs to handle. He recalled with joy how he worked intensely and continuously with all of them, always available on call, any time of the day or night. This is where many explorations on Relativistic Mechanics, Theory of Groups, and Representation Theory, etc. started. After his few years at Rochester during which he quickly went from being and Assistant Professor to an Associate Professor, he was invited at Syracuse in 1964 to be a Professor and Director of the programme on Elementary Particle Physics. During these years he began a collaboration with N. Mukunda whom Sudarshan admired a lot, and this led to the monograph presenting the new perspective on Classical Dynamics from Group Theoretic point of view. The collaborators and proteges of these years continued to interact with him throughout much of his life, often returning to the unresolved issues with ardent persistence. Sudarshan once said that you work in physics because something bothers you. And one cannot but help going back to those themes in trying to resolve them.

Stochastic quantum dynamics and quantum information

Sudarshan sought to understand the origin of the Pauli master equation of Statistical Mechanics from a more fundamental viewpoint to explore whether there are generalizations that remain applicable to quantum systems. These he called 'Dynamical Maps' to imply a generalization from continuum evolution. These papers written in 1960s have been found to be relevant to the questions related to Quantum Information theory in the 1990's.

During the 1970's he returned to these questions, seeking a characterization of most general maps of this kind. With Vittorio Gorini, a postdoctoral fellow, he studied the work of Andrej Kossakowski. They realized that the popularly known Lindblad equation was a simpler version of the previously worked out Kossakowski equation, as indeed referenced by Lindblad. Gorini and Sudarshan collaborated with Kossakowski emphasizing and reworking some of the aspects of this general formalism.

Institutions

After his tenure at Syracuse during 1964 to 1969, Sudarshan moved to the University of Texas at Austin. Within the following decade a galaxy of other luminaries joined the University, notably Ilya Prigogine, John Wheeler, Marshall Rosenbluth and Steven Weinberg. The department grew to be pre-eminent in the areas of fundamental physics such as statistical mechanics, general theory of relativity, quantum field theory and elementary particle physics, but also pioneered a major programme on Fusion Plasma. Jeff Kimble joined as a young professor and set up a laboratory in Quantum Optics. Sudarshan built up and headed the Centre for Particle Theory, with acronym CPT, referring to the fundamental symmetries of Elementary Particle Physics. From 1972 onwards Sudarshan was also a member and Director of the Centre for Theoretical Studies at Indian Institute of Science (IISc), Bangalore, set up to foster interdisciplinary research based on theoretical methods. The association with IISc was held simultaneously with his regular appointment at Austin.

In 1983 upon retirement of Alladi Ramakrishnan, Sudarshan was appointed Director of the Institute of Mathematical Sciences, Chennai, popularly known as Matscience. Sudarshan recalls that he worked to make the functioning of the Institute more professional and in keeping with the international standards. He also got the salaries to become commensurate with those at other institutes of similar stature. There then followed an expansion as worldwide flow of Indian scholars joined the Institute. This association was also held simultaneously with his Austin position, and came to an end after 5 years, in 1988. After that he remained primarily at Austin, visiting India almost every year to give invited lectures.

Over the past decade or so his health had been degrading, though his mind remained ever sharp and his wit remained intact. His continuous companion during his last decades has been his wife and long-time collaborator, G. Bhamathi. He is also survived by two sons. Our condolences go to Bhamathi, and to the rest of his family.

About this obituary

This author had the good fortune of being associated with Sudarshan as a Ph D student during 1982 to 1986, and has fond memories of many interactions, singly or in a group, where both the physics insights as well as his personal wit and warmth regaled us. My thesis was indeed inspired by his suggestions and received some blessing in the form of a small gem of a theorem, but which had very little bearing on the extent and scope of his great works.

The importance of some of his works began to dawn on me when he accepted our invitation to visit IIT Bombay as a Distinguished Visitor on the occasion of the Golden Jubilee of the Institute in 2008 and delivered a set of lectures aimed at a variety of audiences.

In 2014 I undertook to interview him for the 'Face to Face' feature in *Resonance*, meant for a general scientific audience. In the above write-up I have relied on the matters he emphasized to me in the course of this leisurely interview over two days. I am also fortunate to have available to me an older unpublished transcript from around 1982 which outlines the significance of some of his work. I have taken this opportunity to highlight and put in context his contributions that should make the Indian scientific community, and more generally the Indian citizen, proud.

1. This series of so-called 'Rochester Conferences' started by Marshak continues to date, and has become the prime biennial forum of Elementary Particle Physics.
2. Feature Face to Face, *Resonance*, March 2015.
3. In his famous 1905 paper Einstein only used thermodynamic entropy arguments to obtain the integer nature of the energy of light quanta. He did not however provide a derivation of the Planck Law based on this hypothesis.

URJIT A. YAJNIK

Physics Department,
Indian Institute of Technology,
Mumbai 400 076, India
e-mail: yajnik@phy.iitb.ac.in