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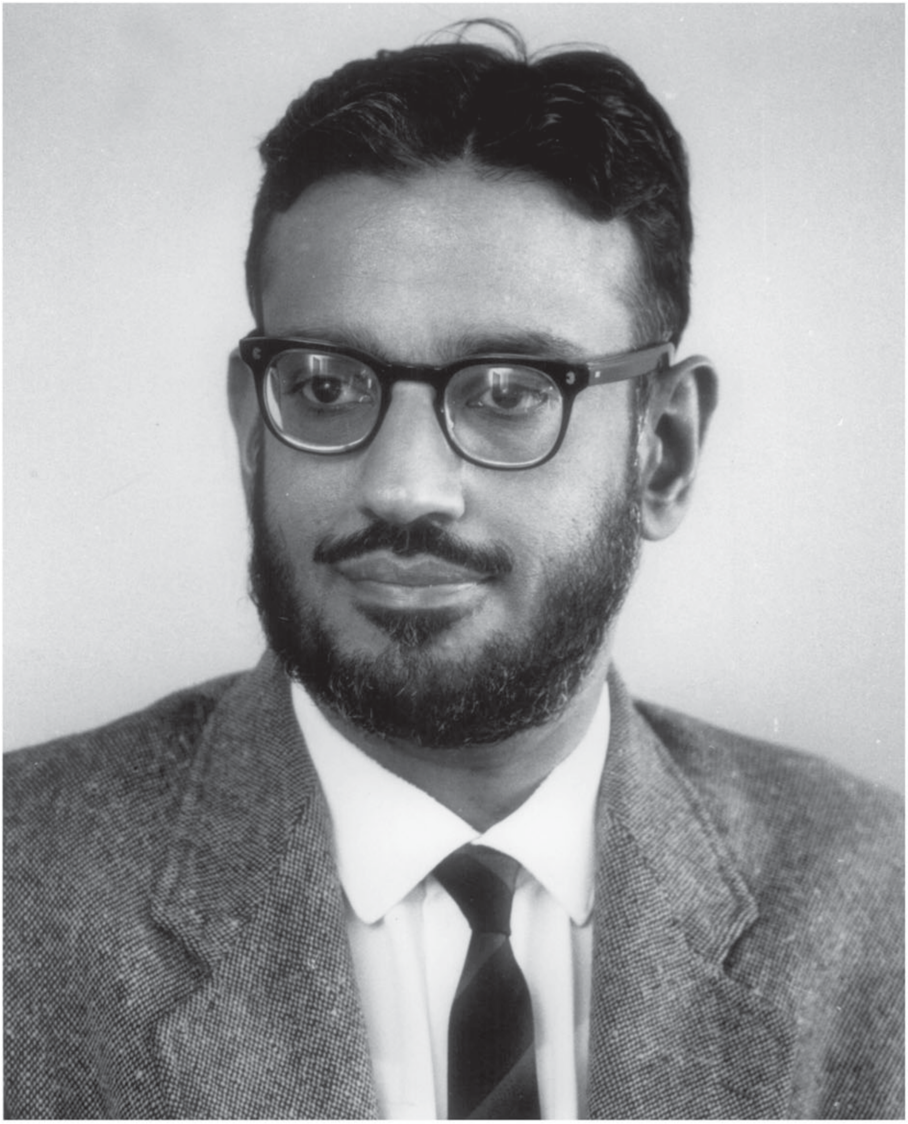

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Elected FRS 1970

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M. G. K. Menon, referred to as Goku, was an outstanding particle physicist and an extraordinary statesman of science. He made his major contributions to particle physics during the tortuous years of the unravelling of the full complexity of the families of elementary particles. It was an exciting but perplexing period, and the elucidation of the complexities of the world of elementary particles took the combined efforts of the experimentalists and the theorists. Goku's contributions were central to establishing what was eventually to become the standard picture of elementary particles. He will be remembered for his studies of the two- and three-body decay modes of the charged kaon that gave rise to the 'τ–θ' puzzle signalling non-conservation of parity. He coined the evocative phrase 'associated production' to describe the creation of kaons and hyperons together in high-energy interactions. He led a team that carried out experiments at great depths underground, and in 1965 they detected an event in which a cosmic-ray neutrino interacted with rock, producing an energetic muon. In the 1980s, with a large detector, also deployed underground, he set a lower bound on the lifetime for the decay of the proton. Menon was a great builder of academic and scientific institutions and a pre-eminent advocate for science. Accordingly, he stimulated and participated actively in building up the scientific and technological infrastructure in independent India, initially as the secretary of the Government of India and subsequently as the minister of state for science and technology. As the president of the International Council of Scientific Unions, he spearheaded its participation in the policymaking body of the United Nations. He was at various times the president of the three leading academies of sciences in India and a founding member and vice-president of the World Academy of Sciences. He was a gentle and loving family man and an energetic and engaged scientific colleague.

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The early years

Mambillikalathil Govind Kumar Menon was born on 28 August 1928 in Mangalore on the west coast of India, the youngest of 11 siblings in a well-to-do, highly educated and talented family. His family called him Goku, combining the first syllables of his given names. His father, Kizhekkapat Sankara Menon, hailed from the historic and commercial town of Telicherry, Kerala, in India, and trained for the Bar in the Middle Temple of the Inns of Court, London. After successful completion of the Bar examination, he returned to Telicherry in 1909, where he married Mambillikalthil Narayaniamma, a well-educated young woman. After a brief period of practice, Sankara Menon entered the judicial services of the Government of India, rapidly rose in the ranks, with appointments in several towns, and was finally elevated to the position of high court judge in Madras.

Goku's education started in earnest at the Good Shepherd Convent in Madras. After evening tea, father and son would spend an hour or more in the garden, playing and talking about a wide variety of topics of general interest and also those pertaining to Goku's studies at school. His mother and other siblings too poured their collective wisdom and knowledge into Goku, which he absorbed without any outwardly visible effort. Upon retirement from the Madras High Court in 1937, Sankara Menon was invited to serve as the legal remembrancer by Sir Donald Field, who was then the chief minister of the Princely State of Jodhpur. Here, Goku matriculated in 1942, joined the Jaswant College affiliated to the Punjab University and graduated, with a BSc degree, in 1946.

Goku was contemplating joining a medical college for a career in medicine and surgery, when a chance encounter with Sir C. V. Raman FRS (Nobel Laureate 1930) dramatically changed his plans. Raman had been invited to Menon's home for dinner, over which, with his exuberance and enthusiasm, Raman convinced Goku to pursue research in physics.

Royal Institute of Science, Bombay

The opportunity to do research came quickly; Goku secured admission to the Royal Institute of Science in Bombay, which had started functioning as a centre for higher learning by about 1920, and started working under the tutelage of Professor N. R. Tawade, a well-known spectroscopist.

The topic chosen for his Master's thesis was the study of high-pressure bands of carbon. His research efforts resulted in his first paper, 'A note on the initial level of the high pressure bands of carbon' (1)*. It begins with a clear statement that the upper level of the electronic bands of carbon had not yet been fixed with certainty, and goes on to detail the points of controversy regarding the upper state of the C_2 molecule that gives rise to these bands. The paper then presents the spectroscopic observations that were carried out in their laboratory and the detailed analysis of the results. Nearly four decades after this paper was written, the issue addressed in the paper was settled as a consequence of experiments with a CO laser operating at 5–6 μm (Little & Browne 1987).

* Numbers in this form refer to the bibliography at the end of the text.

Figure 1. Goku at work in the laboratory under the kindly guidance of C. F. Powell. (Credit: M. W. Friedlander.)

Goku's approach to research was getting set: choose a problem of lasting interest, discuss the current status including the points of controversy, then carry out meticulous observations and interpret the results. This approach that he learnt as a young student propelled him in his later years to make major contributions to science, to national development and to science policy in general. As Goku was experimenting with making photographic plates sensitive to ultraviolet light, Professor P. K. Kichlu of Delhi University advised him to write to Professor Cecil F. Powell (FRS 1949, Nobel Laureate 1950) of the University of Bristol, who had become internationally famous for his discovery of the pion by the photographic method. It was thus that Goku joined Powell's group at Bristol in 1949 to work towards his doctoral degree (figure 1).

Cecil F. Powell, nuclear emulsions and the Bristol School

Several of Goku Menon's major research contributions came during his time at Bristol, and accordingly a brief digression is appropriate here to describe Powell's path to Bristol, the discovery of the pion and the research activities of his group.

Powell moved to Bristol to work at the H. H. Wills Laboratory after a year's research work in the laboratory of Ernest Rutherford FRS in the Cavendish Laboratory, Cambridge, under the direction of C. T. R. Wilson FRS (Nobel Laureate 1927), the inventor of the cloud chamber, which is an instrument to visualize the trajectories of energetic charged particles like cosmic rays and α and β particles emitted in radioactive decay. W. H. Heitler (FRS 1948), who had worked with H. J. Bhabha (FRS 1941) on the 'Passage of fast electrons and the theory of cosmic showers' (Bhabha & Heitler 1937), prompted Powell to follow up the earlier efforts of Blau & Wambacher (1932) to visualize particle trajectories with photographic emulsions. Enthused by his success with recording cosmic ray tracks in photographic plates, Powell continued his efforts to improve the sensitivity of emulsions, which culminated in the ability to record even relativistic electrons in emulsions developed by Messrs Ilford Ltd. From a measurement of the grain density along the track, which depends quadratically on the charge Z^2 and inversely on the square of its velocity $(v/c)^2$, the charge and the energy of the particle could be estimated.

The existence of the Yukawa particle, namely the pion, whose exchange is responsible for the nuclear forces, was established by the Bristol group led by Powell in 1947, through the discovery of events in nuclear emulsions that showed the particle slowing down and decaying into a particle of finite and unique range (Lattes *et al.* 1947, 1948). They called the primary particle the π meson (pion) and the particle emerging from the decay the μ meson (muon). The unique range of the μ meson indicated that the decay was at rest into two bodies. For this discovery, Powell was honoured with a Nobel Prize in 1950, and this was just about a year after Goku joined his famous fourth-floor group in the H. H. Wills Laboratory, which 'was a worthy successor to the Rutherford's School in the 1930s and carried the best traditions of that school' (27).

Goku's research at Bristol—pions, kaons and hyper-nuclei

The bosonic character of π mesons

Goku's experience with photographic techniques in Tawade's lab meant that it did not take long for him to become proficient in the use of similar techniques to study tracks in nuclear emulsions in Powell's laboratory. With remarkable prescience, Powell suggested to Goku that he join Hugh Muirhead and Oliver Rochat to investigate the nature of the interactions of negative pions (π^-) that had come to rest in nuclear emulsions (Lock 1989). A few such events had been observed before (Occhialini & Powell 1947; Perkins 1947), and the aim was to show that the pion was indeed the Yukawa particle whose exchange was responsible for the nuclear forces.

For their investigations, Menon, Muirhead and Rochat made a sandwich of a thin sheet of gelatine between two glass plates coated with layers of nuclear emulsions and got them exposed to beams of pions of energy *ca* 25 MeV at the Berkeley cyclotron (2). By this clever technique, they could identify a nearly pure sample of pion-capture events and reject a small

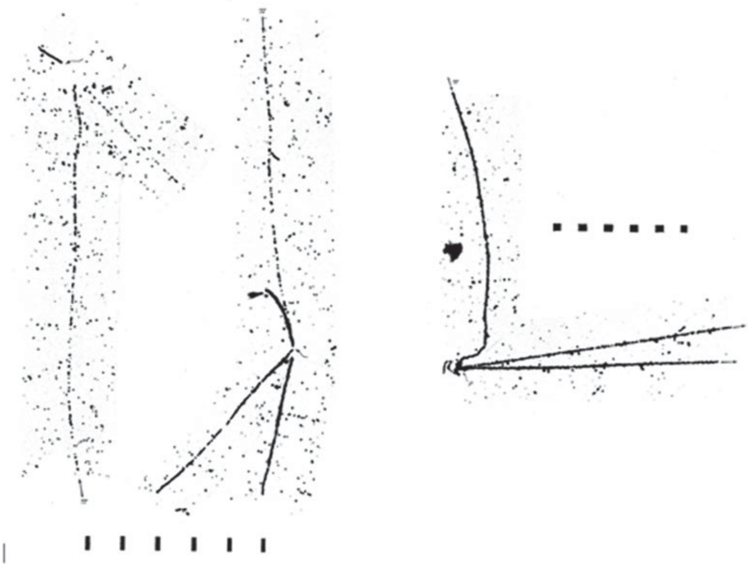

Figure 2. Three nuclear disintegrations following capture of π^- meson are shown. The two on the left panel are most probably by C or O nuclei in gelatin, without any visible silver grains at the location of capture, and the event in the right panel is probably a capture by a Br or Ag nucleus in photographic emulsion (2). (Figure from Powell *et al.* (1959), used with permission from Elsevier.)

background of muon-induced events (see figure 2). Much thought had gone into planning this experiment: Pontecorvo had pointed out that negative muons (μ^-) stopping in dense media do not decay, but are captured preferentially by heavy nuclei followed by the emission of an anti-neutrino during the inverse β-decay process (Pontecorvo 1947); on the other hand, the pion would be captured by all nuclei with equal efficiency, depositing the energy associated with its mass in the nucleus. Having a large sample of events definitely produced by pions would allow one to study the differences in the two capture processes, and permit a search for specific indication that the pion was indeed the exchange particle responsible for the nuclear forces (Marshak 1989). Based on the measurement of the energies of the nuclear fragments emerging from 2500 capture events, their main findings were:

- The energy distribution of the nuclear fragments followed roughly a Maxwellian distribution, confirming the evaporation model at an excitation of 140 MeV.
- The amount of energy estimated for the combined energy of the fragments is *ca* 140 MeV, roughly equal to the mass of the π mesons; there was no indication that an energetic neutrino was emitted in the capture, carrying away energy, as would be expected if the pion were to be a fermion.

With this experiment, Menon *et al*. (2) were able to confirm the bosonic character of pions (π^-), as needed for the Yukawa particle mediating nuclear forces (Marshak 1952).

Scattering effects on particle trajectories and measurements of particle masses

Multiple Coulomb scattering of energetic charged particles on nuclei in a medium causes their trajectories to wander about their straight path. Following the suggestion of Bose & Chaudhuri (1941), much work had been done to show that the mean projected angular deviation of their path is given by

$$\langle|\varphi|\rangle = Kz^{1/2}/pv. \quad [1]$$

Here, p and v are respectively the momentum and velocity of the particle, and z the effective charge of the nuclei in the medium (Williams 1939; Molière 1947; Snyder & Scott 1949). Goku actively participated in an effort to accurately measure the value of the scattering constant K, to show that Molière's theory was confirmed, and assessed the methods of determining the masses of particles by combining the results of scattering measurements with those of grain density along the trajectory, which is a simple function of the velocity of the particle (4–6). This effort paved the way for later measurements of the masses of heavier mesons.

K mesons and hyperons

Within a year of his arrival, Goku was well integrated into the Bristol group and was rapidly growing as a physicist. At that time the only particles that were well known were the proton, neutron and electron, the building blocks of the physical universe, the neutrino, postulated to ensure conservation of energy in β-decay, the positron, which was discovered in cosmic rays and confirmed Dirac's prediction, the muon, constituting the penetrating component of particle that decayed into a proton and a pion. This was later named as Λ^0 and belongs to the cosmic rays, and the pion, the Yukawa particle responsible for the nuclear forces. Some occasional reports of other particles observed in cloud chambers and nuclear emulsions were emerging, indicating that there was a fascinating world of elementary particles yet to be discovered. Goku decided to participate fully in these discoveries.

The first ever indication that there were particles of mass lying between that of the π meson and the proton had come in 1944 through the efforts of L. Leprince-Ringuet and M. L'Heritièr (Leprince-Ringuet & L'Heritièr 1944), who observed a particle of mass *ca* 505 ± 60 MeV in a magnetic cloud chamber, followed by the discovery by G. D. Rochester (FRS 1958) and C. C. Butler (FRS 1961) of two 'V'-shaped events of masses, *ca* 500 MeV and 393 MeV, with large uncertainties (Rochester & Butler 1947). Around the same time, Hopper & S. Biswas (1950) observed a very similar looking event produced by a neutral particle that decayed into a proton and a pion. This was later named a Λ^0 and belongs to the hyperon family. In the autumn of 1948, Powell's group discovered in a nuclear emulsion stack exposed at Jungfraujoch a remarkable event in which a singly-charged particle came to rest and decayed into three charged particles—and called it a τ meson, with a mass *ca* 530 MeV (Brown *et al*. 1949). In 1950 two more such events were discovered by J. B. Harding of Imperial College (Harding 1950). The Bristol group discovered another τ event in a stack of emulsion pellicles exposed also at Jungfraujoch under 30 cm of lead, which had a favourable geometry for making measurements (figure 3). Based on a detailed study of these four τ events and two others that showed decays in to a single charged particle accompanied by one or two neutral particles, Goku, together with P. H. Fowler (FRS 1964), Powell and Rochat (3), drew several important conclusions:

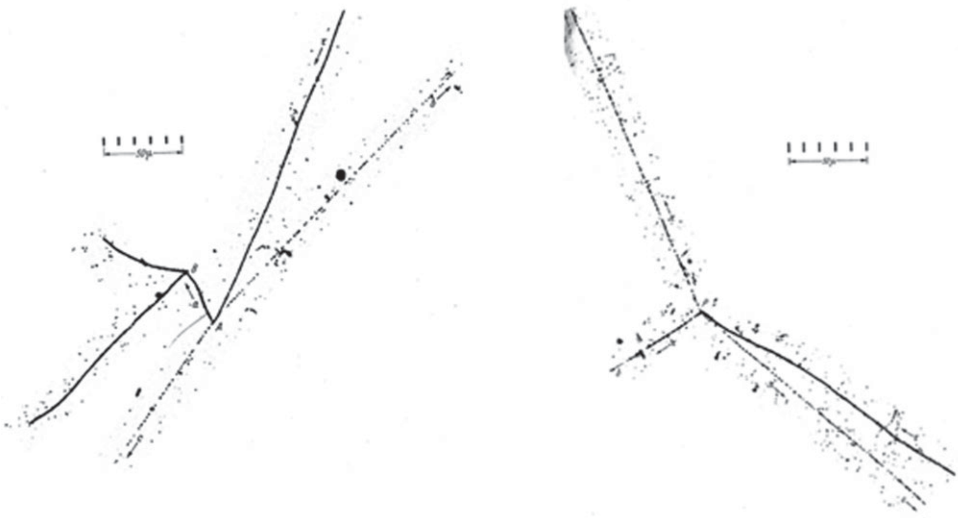

Figure 3. Two events of the decay of K^+ mesons decaying through the τ mode into three pions are shown. In the left panel one of the π^- arising out of the decay is captured by a nucleus, which disintegrates thereafter (Brown *et al.* 1949) (3). (Figure from Powell *et al.* (1959), used with permission from Elsevier.)

- The existence of the heavy charged meson, τ, decaying into three singly-charged particles was confirmed, with a mass of 495 ± 5 MeV (close to the modern value of the mass of K^+ of 493.7 MeV).
- There was a strong indication all three decay products of τ are pions.
- The two particles that decayed, each emitting only one charged particle, were called the κ mesons (O'Ceallaigh 1951) (7).
- The lifetime of the τ and κ mesons was greater than *ca* 10^{-9} s (i.e. very long!).
- The τ and κ mesons were created in cosmic ray interactions at rates similar to the production of pions.

This paper clearly established the existence of heavy mesons and that these mesons are produced in nuclear interactions by energetic cosmic ray nuclei in a manner similar to the production of π mesons (which carry the nuclear force), but have decay lifetimes many orders of magnitudes greater than the lifetimes estimated using the nuclear coupling constants given by Yukawa (10^{-9} s instead of 10^{-22} s). This conundrum of strong production and weak decay was solved only two years later by Murray Gell-Mann (ForMemRS 1978) (Gell-Mann 1953) and soon thereafter independently by Nakano & Nishijima (1953). As we will see, it took even longer for the resolution of the puzzle of whether the κ and τ could be alternative decay modes of the same particle (Lee & Yang 1956).

With these important discoveries in hand, Cecil Powell organized an international conference in London for a few days starting on 18 December 1951, for which Goku and O'Ceallaigh worked hard to collect more events and carry out additional measurements. Their presentations (7, 12) are collectively summarized as:

1. The V-particles seen in the cloud chambers belonged to the same class as those discovered in nuclear emulsions.
2. In the decay of one of the κ mesons studied by O' Ceallaigh (12), the emerging charged particle could be identified as a μ meson.
3. Some of the κ and V events could represent alternative decay modes of the same meson, decayed to three charged particles, $\tau \to \pi^{+}\pi^{-}\pi^{+}$.
4. The existence of the τ meson was well established, with a mass of *ca* 495 MeV.
5. The measurements of the mass of the κ meson yielded an average mass of *ca* 640 MeV with a large uncertainty of *ca* 125 MeV.
6. In two cases of κ decay, the secondary particle arising from the decay could be identified with certainty as a muon.
7. The momentum distribution of the μ mesons showed a large spread, indicating that decays were of the type $-\kappa \to \mu^{+}+a^{0}+b^{0}$, where a^{0} and b^{0} were likely to be π^{0} and ν.
8. The κ particles were about 10 times as numerous as the τ particles.
9. Some of these κ particles could have an alternative decay mode $-\ \kappa \to \pi^{+}\pi^{0}$.
10. The decay lifetime of both κ and τ mesons were longer than *ca* 10^{-9} s.

In items 3, 7 and 9 we see that the same particle decays either into three particles or into two particles; arguments based on symmetry should forbid this. We see the first glimpse of the τ–θ puzzle, which will be discussed later.

Goku Menon's PhD thesis

In October of 1952 Goku submitted his thesis, 'The tau, kappa and chi particles', for the award of a PhD degree by the University of Bristol (8). In the thesis, his attempt was to include the data on all available events up to the time of writing, re-measure them if possible and then provide a comprehensive assessment.

The τ meson

By noting the coplanarity of the three particles emitted in τ decay, Goku showed that the measurements of their individual momenta implied that the missing momentum was less than 10 MeV/*c*, far less than the typical values for decay into four bodies. Thus, it was clear that only the three observed particles were involved in the final state.

By a clever application of momentum conservation, he showed that the measurements of momenta and angles between the three particles implied that if one of them were shown to be a pion, all of them ought to be pions. Then, by showing that large numbers of particles arising from the decays were pions, either by measurement of the mass or by the properties of their capture events, he could assert that all the particles arising from τ-decay were indeed pions.

Careful measurements showed the total kinetic energy of the three pions emitted in the decay, $Q = 75 \pm 3.5$ MeV. Adding this to the masses of the three pions yields $m_{\tau} = 495 \pm 3.6$ MeV, close to the modern value *ca* 493.67 MeV.

From a personal communication with M. J. Jacobson in 1952, Goku knew that the decay $\tau \to \pi^{+}\pi^{+}\pi^{-}$ was forbidden if the τ meson was a scalar particle; however, when he plotted the spectral distribution of the pions, he found it to be uniform in configuration space, i.e. purely statistical! One had to wait another eight months for a deeper analysis by R. H. Dalitz (FRS 1960) to understand the spin and parity of the τ meson, an aspect of the τ–θ puzzle (Dalitz 1953; Fabri 1954), and it took several more years before it could be resolved completely (Lee & Yang 1956).

By considering the energies of the heavy mesons, the length of their flight paths and the uniformity of the location of the decay events in the emulsion stack, it was estimated that the lifetime of heavy mesons was greater than 10^{-9} s. This is the basis for the conundrum of strong production and weak decay noted earlier.

Kappa and chi particles

Goku had on hand 13 κ and χ particles for his study, 11 discovered by Bristol and one each by the Paris (Crussard *et al.* 1952) and Milan groups (R. Levi-Setti and A. Lovati, pers. comm. with Goku). Microphotographs of a pair of these events are shown in figure 4; each of these shows a particle coming to rest in nuclear emulsions and emitting a single charged particle and one or more neutral particles. The particle was called a κ meson when the decay was to more than two neutral particles and a χ meson when it was a two-body decay. (Today we know, of course, that they are all the same particle, the K meson, or the kaon.) The analysis of the measurements on these events is summarized below:

- The direct measurements on the primary track yielded masses with a peak around the τ mass *ca* 511 MeV with a tail extending up to 740 MeV.
- For $m_\kappa = m_\tau$, two-body kinematic analysis yielded $p\beta$ of the charged particle of about 216 MeV and about 170 MeV for the decay into $\mu^+\nu$ and $\pi^+\pi^0$, respectively. The heavily suppressed e+ν channel is neglected (Ruderman & Finkelstein 1949). With this method, Goku could identify two or perhaps three of these events as arising from three-body decays $K \rightarrow \mu n_o \nu$, where n_o is a neutral particle, probably a π^0, and ν is the neutrino. In modern parlance these are called Kμ3 decays. Two of the events (χ meson) could be attributed most probably to $K \rightarrow \mu\nu$, and three others had $p\beta$ clustering around *ca* 170 MeV/c and were therefore consistent with the decay mode $K^+ \rightarrow \pi^+\pi^0$.

Adding suggestions for future experiments and some general comments on these results, Goku submitted his thesis for the degree of PhD to the University of Bristol in October 1952. The submission of the PhD thesis, and earning the degree in January 1953, marked an important milestone in Goku Menon's career. By that time he had written joint papers with eight of his senior colleagues at Bristol, and his PhD thesis was an impressive effort: it set the stage for understanding K meson physics by showing their strong production and weak decay characteristics, establishing the existence of the decay modes $\tau^+ \rightarrow \pi^+\pi^+\pi^-$, $\kappa \rightarrow \mu^+\nu\ \pi^o$ and the possible existence of $\chi^+ \rightarrow \pi^+\pi^0$ of the K^+ meson. Accordingly, Goku received the Senior Award of the Exhibition of 1857, generous financial support that enabled him to continue his research work at Bristol and to participate fully in the further developments of K meson physics.

On 29 January 1953, Powell organized a second international meeting, under the auspices of the Royal Society in London, to discuss V-particles and heavy mesons. After the inaugural address by Powell (1954), Goku and O'Ceallaigh (12) reiterated the points made in Goku's thesis, along with additional observations, including 11 τ decays. Commenting on their paper

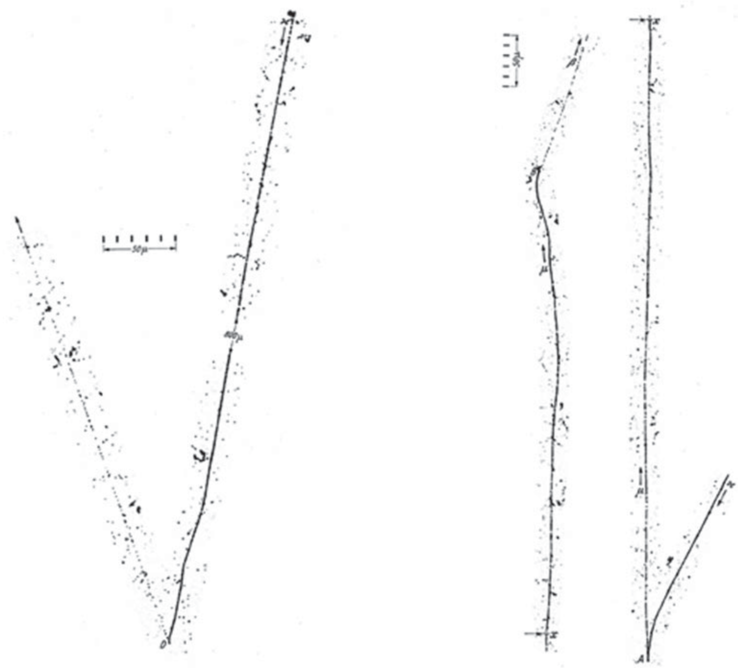

Figure 4. Two examples of the Kμ3 mode of decay are shown. These were referred to as the κ mode in early literature. In the event on the left panel, the muon arising from the decay can be followed until it is arrested in the emulsion, and decays emitting a β ray. (Figures from Powell *et al.* (1959), used with permission from Elsevier.)

indicating that the same particle had two modes of decay (one to two pions and the other to three pions), Marshak remarked that 'this was an excellent paper' (with its anticipation of the θ–τ dilemma!) (Marshak 1989). Here, θ refers to the neutral counterpart of χ; Dalitz, who was present at this meeting, subsequently contributed importantly towards its resolution (Dalitz 1982; Aitchison & Llewellyn Smith 2016).

Near the end of 1952, Michael Friedlander, with a Master's degree from Cape Town, South Africa, joined Powell's 'fourth-floor group' and became a close collaborator of Goku, and a series of about 15 joint papers emerged during the next four years (9–11, 13–23) pertaining to K mesons and hyperons. Before summarizing these findings, the scheme devised by Gell-Mann to theoretically understand some of these findings is introduced.

Gell-Mann's strangeness quantum number

In 1953, Gell-Mann (1953) extended the idea of isospin I, which had been introduced earlier to understand the charge independence of the nuclear forces. In this scheme, the nucleons, namely the proton and the neutron, are assigned $I = ½$, with $I_3 = \pm ½$, and the three pions, π^+, π^-, π^0, are assigned $I = 1$, with $I_3 = \pm 1$ and 0, respectively. The electrical charges of these particles are given by the formula

$$Q = B/2 + I_3. \quad [2]$$

Here, B refers to the baryon number. Note that the formula correctly reproduces the charges. Gell-Mann extended this scheme by assigning another new quantum number, strangeness S, which is $+1$, for the new mesons, and -1 for the more massive new particles like Λ^0 and $\Sigma^{\pm,0}$, which had been discovered in cloud chambers and also in emulsions (e.g. see Brown *et al.* 1989). The isospin assignments were ½ for τ^+, κ^+ and K^0, 0 for Λ^0, and 1 for the Σ particles. The equation [2] when modified as

$$Q = (B + S)/2 + I_3 \quad [3]$$

correctly reproduces the charges of all the baryons and mesons, old and new. Moreover, the formula predicted the existence of new particles, which were discovered later. The same scheme was independently suggested by Nakano & Nishijima (1953), but slightly later. The conundrum posed by strong production of heavy mesons, contrasted by their slow decay, gets resolved with the additional prescription that strangeness is conserved in strong interactions, but is violated in weak interactions. The production of heavy mesons takes place in high-energy collisions between nuclei mediated by strong interaction, and they must be produced in pairs, either with their anti-particles or in conjunction with more massive particles like Λ^0, which possess $S = -1$, so that the net strangeness is conserved. On the other hand, their decay into pions or muons is mediated by weak interactions, and the strangeness is not conserved.

International conference on cosmic rays at Bagnères de Bigorre

The cosmic ray conference was organized through the untiring efforts of Louis Leprince-Ringuet and held during 1–6 July 1953; it is considered by many to be of equal importance to the Solvay Congress of 1927 (Cronin 2011). It was well-attended, with over 20 experimental groups from across the world reporting results, with special emphasis on unstable heavy particles. There were also a few theorists, notably Homi Bhabha and Richard Dalitz. The high point of the meeting was the emergence of the τ–θ puzzle, with outstanding contributions from the Bristol group, especially the paper by Goku with O'Ceallaigh, confirming their earlier results (12), and the paper by Robert Thompson of Indiana University determining the mass of the θ^0 meson (same as χ^0), which decays into $\pi^+\pi^-$ (Thompson *et al.* 1953). It was here that Dalitz presented for the first time his theoretical analysis (Dalitz 1953) showing that the spin and parity of the τ meson was 0^-; a full and detailed description of his analysis is given by J. R. Aitchison and C. Llewellyn Smith (FRS 1984) (Aitchison & Llewellyn Smith 2016). The word parity refers to the symmetry of quantum systems under reflection; if this symmetry is valid we cannot distinguish between the actual phenomena from their mirror image, but if it is not a good symmetry, then we can. Because of our conditioning in the natural world, we tend to believe that all physical phenomena obey this symmetry. If θ^0 and χ were the same particle as τ, but with alternate decay modes, they would have the same spin and parity as τ, namely 0^-. On the other hand, as they decay into two pions their parity ought to be $+$. This was the crux of the τ–θ puzzle. Both could not be true, unless conservation of parity was violated in the decay process. Here was a quantum phenomenon; namely, the decay of an elementary particle that violated the symmetry of parity conservation, which until then was considered to be universally valid. Accordingly, there was great reluctance to conclude that τ, χ and θ were the same particle.

At the end of the conference, Bruno Rossi clarified the confusing nomenclature adopted by different groups, summarized the main results and declared that the two- and three-body decays were alternative decay modes of the same particle until shown otherwise. It was here that Leprince-Ringuet coined the name 'hyperon' for baryons possessing the strangeness quantum number.

Bhabha took the same point of view as Rossi on τ and θ being alternative decay modes of the same particle, and reported the key results of the conference in Bagnères at the International Conference of Theoretical Physics in Kyoto and Tokyo held in September 1953 (Bhabha 1953). After his presentation, there was a lively discussion in which Bhabha, Marshak, Heitler, C.-N. Yang (ForMemRS 1992; Nobel Laureate 1957), A. Pais, E. Amaldi (ForMemRS 1968), and R. E. Peierls FRS participated. Yang wanted to know how well the experiments had established that τ and θ were alternative decay modes of the same particle. These discussions are of interest in the context of the resolution of the τ–θ puzzle four years later, when the identity of the two had been well established with good statistics (Brown *et al.* 1989; Ceolin 2002; Olivotto 2009). Yang and T. D. Lee proposed that parity was violated in weak interactions in general, including in the β decay process of radioactive nuclei (Lee & Yang 1956). Today, we know that τ, κ, χ and θ are all alternative decay modes of the same particle, depicted as K.

As figure 5 shows, these conferences were a perfect opportunity to forge friendships and collaborations with others in the community.

Further studies of K mesons and hyperons

As noted earlier, Goku's collaboration with Friedlander resulted in several important results (9–11, 13–23):

- They showed that the production of K^- by cosmic rays was suppressed significantly below that of K^+ (which was understood later by noting that the production of K^- has a significantly higher threshold).
- They carried out improved measurements of the mass of Λ^0, which yielded $m_\Lambda = 1114.6 \pm 0.22$ MeV—very close to the modern value, 1115.60 MeV.
- A very rare event, $-K^+ \to e^+ +$ neutral particles, was discovered: e^+ was identified as such, by the large-angle scattering it suffered while emitting a bremsstrahlung gamma ray.
- In a major effort involving the study of *ca* 10 000 cosmic ray interactions, several events were found depicting the capture of K^- mesons by nuclei, leading to the production of Λ^0 and Σ^0 hyperons. In the same paper (16), Goku coined the evocative phrase 'associated production' to describe their results, which implied the requirement that a strange particle be produced together with another particle of opposite strangeness in order to conserve strangeness. The reactions they reported are called cross-channel reactions, and they do conserve strangeness. The event $\pi^- + p \to \Lambda^0 + \theta^0$, recorded in a hydrogen diffusion chamber operating at the Brookhaven accelerator, had been reported earlier by W. B. Fowler (Fowler *et al.* 1954). This is the

Figure 5. Enrico Fermi ForMemRS demonstrating the game of ‘hand football’, or *Gitoni* in Italian, during the Varenna Summer School (1954). From left, George Clark, Goku Menon, Enrico Fermi and Eduardo Amaldi. (Photo credit: Juan G. Roederer.)

forward channel reaction. Goku continued to use the phrase ‘associated production’, including it in some of the titles of his papers on K mesons and hyper-fragments (nuclei in which a Λ^0 has replaced a neutron).

Goku had the opportunity to report on his work at the Fifth Rochester Conference held from 31 January to 2 February 1955. Marshak, one of the organizers of the meeting, remarked that

> it was therefore no surprise to meet Goku Menon at the Fifth Rochester Conference, as the representative of the Bristol Group. Menon gave a fine report on several decay modes of the K mesons and hyperons being measured at Bristol including one possible example of the cascade hyperon decay [$\Xi^- \to \Lambda^0 + \pi^-$, followed by $\Lambda^0 \to p + \pi^-$], and in response to a question from Oppenheimer—as to whether there was clear cut evidence of associated production of K particle and hyperon—he quickly furnished a list of a half dozen cases (Marshak 1989).

In summary, the experiments carried out by Goku in collaboration with the Bristol group resulted in showing that the pion is a boson, led to the invention of the strangeness quantum number, and provided the stimulus for the discovery of parity violation in 'weak' interactions.

The culmination of Goku's efforts during the Bristol period is well described by Charles H. Townes (ForMemRS 1976, Nobel Laureate 1964):

> In the first half of the 1950s, I was serving as the chairman of the Department of Physics at Columbia University . . . Particle physics was just coming into its own as a major forefront field, and we searched everywhere for the absolutely most promising young faculty possibility in this relatively new field. The answer was MGK Menon, . . . We found him very impressive . . . and hoped that he would accept our invitation to become a new professor in the Columbia University [Goku declined the invitation]. While Columbia failed to gain an outstanding physicist, I felt at that time that Goku's decision was at least conscientious and thoughtful. It is clear today that it was also wise. Although he would have accomplished much at Columbia, the decision has resulted in important contributions not only to India, but also to the worldwide science, and scientific statesmanship (Townes 1989).

Not only was the Bristol period an exciting and scientifically productive one for Goku, but it was also filled with warmth, fraternity and friendship with his fellow scientists. This was also where Goku met and married Miss Indumati Patel, who was working towards a degree in philosophy.

Tata Institute of Fundamental Research

Not long after his visit to Columbia University, Goku received an invitation from Homi Bhabha to join the Tata Institute of Fundamental Research (TIFR) in Bombay, India. Indu and Goku sailed to India by the end of 1955, and Goku joined TIFR, which had been founded by Bhabha in 1945 in Bangalore. By 1955 it had moved to Bombay and was located at the Old Yacht Club. Already within its first 10 years it had become well known for cosmic ray studies, theoretical physics, nuclear physics and mathematics. At TIFR, Goku seamlessly integrated himself with the programmes initiated earlier by Bhabha in particle physics and cosmic rays: (1) with detectors deployed deep underground, led by Professor B. V. Sreekantan; (2) with nuclear emulsions, led by Bernard Peters (previously from Rochester, New York) and by Roy Daniel (PhD from Bristol, UK); (3) with electronic detectors carried to high altitudes with balloons, led by Professor G. S. Gokhale (figure 6).

Bhabha found in Goku a kindred spirit, and asked him to shoulder progressively greater responsibility in the affairs of the institute. This brought Goku into closer contact with Bhabha, and, equally importantly, with J. R. D. Tata (FRS 1973), under whose joint influence the innate qualities in Goku matured. This certainly did free Bhabha's time, which he could then devote to the development of atomic energy for peaceful purposes (such as the generation of power), and production of radioactive isotopes for medical applications, and also to conceptualize a broad framework for the growth of electronics, computer sciences and information technology, defence capabilities and space activities in India. Concomitantly, this also did place a heavy burden of administrative responsibilities on Goku's shoulders. He took up all responsibilities that were thrust upon him with an unassuming and selfless manner, while he continued to make important contributions in the research and development activities of the three groups he had joined.

Figure 6. A. G. W. Cameron (facing away) lecturing during an International Symposium (*ca* 1968) organized at the Tata Institute of Fundamental Research. In the front row from the left are seated: B. Peters, W. B. Fowler, C. F. Powell, V. Sarabhai, Yash Pal, Goku Menon, G. Swarup (FRS 1991) and R, Cowsik. (Credit: TIFR Archives.)

Scientific ballooning in India

Cosmic ray studies with instruments carried to high altitudes by balloons were initiated in India by Millikan in 1942 (Millikan *et al.* 1942) and were continued by Bhabha for the study of the penetrating component and other aspects of cosmic rays (Bhabha *et al.* 1945). Goku continued the effort with his colleagues V. K. Balasubrhmaniam and G. S. Gokhale, making major advances in the fabrication and launch capabilities. Over the years, the TIFR ballooning facility has served not only the needs of scientists in India and the Indian Space programme, but also those of scientists from the USA, UK, Italy, Germany, Japan and Russia on a few occasions (Gokhale 1989).

Cosmic ray and particle physics deep underground

Bhabha had initiated the experimental study of the penetrating component of cosmic rays at TIFR, *ca* 1950, as the PhD research project for his newly joined student B. V. Sreekantan. Two more students, S. Naranan and P. V. Ramanamuthy, joined the effort a little later. A cosmic ray hodoscope was set up deep underground in the mines of the Kolar Gold Fields, in Karnataka, India, with which they measured the angular distribution and the rapidly decreasing intensity of muons down to a depth of *ca* 300 m. These studies got a great boost when Goku joined the group in 1959, and by the subsequent participation of S. Miyake and others of Osaka City University, Japan. The observations indicated that the flux of muons at depths of about 3 km underground was very small, comparable to the qualitative estimates of the flux of muons induced by neutrinos arising from decay of mesons generated by cosmic rays in the Earth's atmosphere. This opened up the possibility of detecting cosmic ray neutrinos deep underground (24, 25). In parallel, Cowsik, Pal and Tandon (Cowsik *et al.* 1963, 1966) had made detailed calculations of the spectral intensities of neutrinos of both electron and muon types generated by cosmic rays in the Earth's atmosphere, and estimated the expected neutrino-induced muon intensities underground. Around the same time, the cosmic ray group at Durham, UK, led by A. W Wolfendale (FRS 1977), joined the collaboration. This international collaboration announced its first detection of a cosmic ray neutrino in 1965 (26). At the same time, the efforts led by Frederick Reines also succeeded in detecting an event induced by cosmic ray neutrinos in the gold mines of Witwatersrand, South Africa (Reines *et al.* 1965). A continuation of such studies in Japan by a team led by Masatoshi Koshiba discovered the phenomenon of neutrino oscillations with a very large detector, and this discovery was recognized by the award of the Nobel Prize.

In the early 1980s, soon after the Grand Unified Theories predicted the possibility of the decay of the proton, Goku, continuing the collaborative effort deep underground, set a lower limit on the lifetime for the decay of protons of *ca* 2.10^{31} years (28), improving on the earlier results (Cowsik & Narasimham 1980).

Studies with nuclear emulsions—stepping stone to bubble chambers and colliders

During his Bristol years, Goku had established a close friendship with Dr William Owen Lock, who had moved to CERN in 1959 and had rapidly advanced to positions of leadership. This facilitated forging collaboration between TIFR and CERN, which progressively led to highly successful alliances such as L3 experiments at the large electron–positron collider, and the CMS, ALICE and Atlas experiments at the large hadron collider in recent decades. Important results that emerged from these collaborations include the discovery of the Z boson and the measurement of its mass and width, and the momentous discovery of the Higgs boson.

Increasing responsibilities

Goku was indefatigable and was known for his attention to detail and the meticulousness with which he assessed all the background material before taking a decision. He rapidly advanced to the position of dean of the Faculty of Physics, followed by his elevation to the position of the deputy director (physics). TIFR grew rapidly in areas as diverse as biological sciences, radio astronomy, solid-state electronics and geophysics, and, to quote Sreekantan, 'Menon was the guiding spirit behind these developments' (Daniel & Sreekantan 1989).

It was soon after this that a great tragedy befell the Indian scientific scene: on 24 January 1966 Bhabha was killed in an air crash over Mont Blanc. The chairman of the Governing Council of the TIFR, J. R. D. Tata, appointed Goku as the next director of the institute, which carried with it not only the burden of responsibility of guiding an internationally famous institute to greater heights but also the more challenging one of realizing the dream Tata had shared with Bhabha of a scientifically advanced and technologically capable India.

> 'It goes to the credit of Menon that during the crucial period following Homi Bhabha's death, he was not only able to maintain and further the high standards of basic research at the Institute but also encourage the Institute to undertake major projects of national relevance in the fields of electronics, computer science and material science . . . The Institute became much more broad-based and the expertise that had been developed as a part of its research programme became available for national use and development' (Daniel & Sreekantan 1989).

Goku was elected Fellow of the Royal Society in 1970, in recognition of his outstanding contributions to particle physics and for the studies in cosmic rays.

On the national and international arena

During the early years of his directorship of the TIFR, Goku was invited by Raman to play a central role in the Board of Trustees of the Raman Trust. When Raman died after a brief illness in November 1970, Goku was involved with persuading V. Radhakrishnan (Rad) to accept the directorship of the Raman Trust and build up the institution with the full support of the Government of India. Today, the Raman Research Institute is doing extraordinarily well in the fields of radio astronomy and atomic and condensed matter physics.

Similarly, after the tragic death in December 1971 of Dr Vikram Sarabhai, chair of the Indian Space Research Organization, Goku, who was already holding the positions of chair of the Electronics Commission and secretary to the Government of India Department of Electronics concurrently with the directorship of the TIFR, was asked by Prime Minister Indira Gandhi to shoulder the additional responsibilities of chair of the Indian Space Research Organization and directorship of the Physical Research Laboratory in Ahmedabad. While agreeing to hold these additional responsibilities briefly, Goku prevailed upon Professor Satish Dhawan, of the Indian Institute of Science, to give up his professorship and accept responsibility of guiding the Indian Space Research Organization as its chair. The success of the space programme in India and the formation of the Space Commission owes as much to Dhawan’s tremendous abilities as to Goku’s perspicacity and persuasiveness. Goku had at various times occupied the position of president of the three academies of sciences in India: the Indian Academy of Sciences, the Indian National Science Academy (INSA), and the National Academy of Sciences, India (NASI). During his presidency, and through his continued association with them, these academies vastly increased their scope and engagement with society.

Cecil Powell was a great internationalist, and this trait was imbibed by those working in his laboratory, including Goku, who was deeply committed to achieving human progress through science. There are not many scientists who are deeply committed to the concept that it is only through the growth of science that the major problems facing humanity can be solved, not only within one’s own country but also worldwide, even in the poorest of nations. Abdus Salam FRS was certainly one of them. Both Goku and Salam were admitted into the Pontifical Academy of Sciences in 1981, and on this occasion, over a quiet dinner with Salam, Goku raised the possibility of setting up an international academy and discussed how this would energize the scientists in developing countries, confirm their academic credentials and allow them to spread science and scientific method in their respective countries. Also, such a body ‘could assume responsibility for the advocacy of science, establish standards of excellence, and promote social, cultural and economic development’. It was thus that the idea of the World Academy of Sciences (TWAS) was born, and realized in 1983, with luminaries from nations across the world as the founding fellows of the academy.

From among the long list of his outstanding achievements, one must include the key role Goku played in saving the Silent Valley from ecological disaster. The Silent Valley is a dense tropical forest, occupying about 30000 hectares in the Western Ghats of Kerala. This area is rich in rare flora and fauna, and constitutes an important reserve of diverse life forms and a large gene pool. Primitive nomadic tribes live along its outskirts. The threat to the Silent Valley came in the form of a resolution by the Kerala Assembly, in about 1976, to dam the Kunthipuzha River, which would flood a significant fraction of the valley, but would provide the opportunity for generating about 250 MW of hydroelectric power and also to irrigate some 10000 hectares of land. Environmentalists across India, supported by international groups and scientists, launched a strong opposition to the project. A veritable war raged on between the Kerala government and the opposition. To resolve the impasse, Prime Minister Indira Gandhi appointed a committee of eight persons, four chosen by the Kerala government and four by the Government of India, with Goku in the chair (Swaminathan 2016). The committee was to report its recommendations speedily, in about three months. This was too short a time to fully assess all the pros and cons of the issue and, more importantly, for the rigid stance taken by the two sides to thaw. This is where Goku's statesmanship came to the fore. Such was his objectivity while hearing the arguments and assessing the problem that both sides felt that his decision would be agreeable to their cause. The decision came slowly but surely, with a carefully drafted evaluation in favour of the environmentalists, and the Silent Valley is still there for all to enjoy.

In 1988 Goku was nominated president-elect of the International Council of Scientific Unions (ICSU), and he served as its president for two full terms. Around the same time he was nominated as a member of India's parliament and minister of state for science and technology, and for education. Dr Julia Marton-Lefèvre, the Hungarian-born French–US environmentalist, whom Goku had met several times at TWAS, became the executive secretary of ICSU in 1989. She wrote recently that 'Goku Menon's period at ICSU also marked a high point in ICSU's history by opening the way for the organization to use excellent scientific knowledge to influence policy'. They formed a very good combination, complementing each other. She adds: 'Thanks to Professor Menon's ability to influence at the highest levels, we managed to convince the UN bureaucracy to include a chapter, hitherto not on the list of contents of Agenda 21, on "Science for Sustainable Development" representing ICSU's view of the key role of science in the important journey toward sustainability' (Marton-Lefèvre 2016).

A joyous and fruitful life

Such sterling human qualities, coupled with high intellect and administrative judgement, in Menon were recognized widely; selected lists of appointments, awards and honours are provided elsewhere (Cowsik 2013; Sharma *et al.* 2016). The fruits of his labours are seen in the technological and academic institutions in India and across international organizations; these stand in testimony to his remarkable life and achievements. He continued to serve the nation and international community of scientists with distinction in many ways to the very end.

Goku was a gentle and loving family man. He leaves behind his wife Indu, son Anant Kumar Menon, professor of biochemistry at Weill Cornell Medical School, New York, and his daughter Preeti Vaid MD (Radiology), New Delhi.

Awards

1953–1955 Senior Award of the Royal Commission for the Exhibition of 1851

1960	Shanti Swarup Bhatnagar Award for the Physical Sciences (Council of Scientific and Industrial Research, India)
1978	Cecil Powell Medal of the European Physical Society
1985	C. V. Raman Medal (INSA, India)
1985	Padma Vibhushan (Presidential medal, India)
1997	Abdus Salam Medal (TWAS, Trieste, Italy)

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