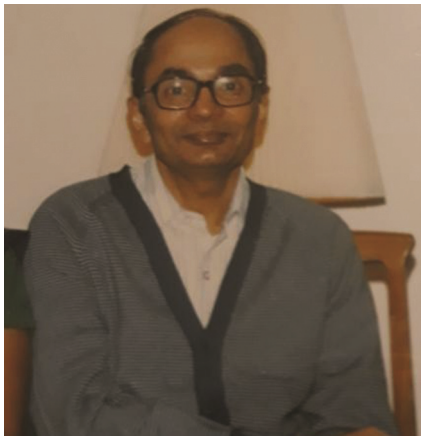
Aiyasami Jayaraman (1926–2022)

Dr Aiyasami Jayaraman, an iconic world figure in the field of high-pressure physics, who worked in the Bell Telephone Laboratories, USA (generally known as Bell Labs) for the bulk of his professional career, passed away on 1 April 2022 at the age of 95, in Phoenix, Arizona, USA. He was intimately associated with physics in India; he initiated and was involved with high-pressure research in several groups there for more than four decades.

Jayaraman (known as AJ to his friends and colleagues) was born on 5 December 1926 in Marathur, a village near Kumbakonam in the Cauvery delta of Tamil Nadu, India. After elementary education in the village school, he went to a small town called Kuttalam for high-school education and then to Annamalai University in Chidambaram for intermediate education. Here he also attended stimulating lectures on cosmology, radioactivity and spectroscopy delivered by S. Ramachandra Rao, a professor of physics there and a former student of C. V. Raman. Jayaraman then joined Pachaiyappa's College in Chennai (then Madras) and obtained a B.Sc. degree in chemistry in 1946.

Jayaraman then spent two years at the College of Engineering in Guindy, Chennai, as a research scholar and also served as a Demonstrator in chemistry there for over a year. He did both research and performed duties as a Demonstrator. The engineering students were required to have some exposure to physics, chemistry and geology and to conduct lab experiments. The duty of the Demonstrator was to supervise their lab work and also do some teaching. Because of this, he picked up quite a bit of knowledge in electrical and mechanical engineering. He also did some research on catalysis under R. Srikantan, a physical chemist. In 1947, he listened to a deeply impressive and inspiring talk by Raman on the Faraday effect, given at Loyola College, Chennai. Jayaraman was a regular visitor to the Connemara Public Library and the Madras University Library and educated himself in physics in this manner.

Jayaraman had entertained for long the thought that he wanted to work with Raman. On an off chance, when he was in Bangalore in 1949, he called up Raman, was interviewed by him, and was offered a job as a Research Assistant (on probation for six months). Jayaraman was associated with Raman as his co-worker (first as a Research Assistant, then as an Assistant Professor in the Raman Research Institute (RRI), and then as its Assistant Director) for more than 11 years. This was the formative period of his professional life. Jayaraman not only absorbed physics from this association, but also Raman's values in physics research, e.g. thoughtful experimentation, the necessity of simple overarching physical explanations, a sense of beauty in physics and a positive, can do, never say die spirit. For example, there was no electricity in RRI for the first two years. Raman said that research should not



wait for the arrival of electricity and they performed extensive research in optics using sunlight as the source. The overall thrust of this research was scientific description and explanation of the beautiful natural optical phenomena in minerals, gemstones, butterflies, etc. One of the first materials that they investigated was labradorite, a feldspar which showed spectacular iridescent colour when viewed in certain directions. Raman devised an ingenious way to study this, using a beam of sunlight and a white card held before the sample, to the side. The study immediately revealed the nature and geometry of the optical effect in relation to the crystallographic orientation of the sample. From a detailed exploration they could establish that the colour had its origin in the physico-chemical aspects of this material and the precise manner in which the parts of the samples were oriented. The double halo seen with some specimens was connected to twinning in the matrix sample, and its geometry and crystal chemistry. Jayaraman also worked on moonstone, a semi-precious gem, which exhibited fine blue diffusion when viewed in certain directions. From the size, shape and colour of the halo, Raman was able to obtain a rough estimate of the size and shape of the particles responsible for the effect. As Jayaraman says: 'During the observation sessions I learnt a whole lot of crystal optics, for Raman would be talking all the time about the underlying physics. This is the best way to learn a new subject for me.' At this time Raman was interested in the coloured reflections exhibited by potassium chlorate crystals. He and Jayaraman found that the crystals which showed the effect were multiply twinned in a perfectly periodic manner, so as to cause Bragg-like reflections and that the colour was highly monochromatic. They could determine crystal orientation for the twins from the Laue diagram. In the modern context this would be considered a photonic crystal, for the periodicity is of the order of the wavelength of light. This is a beautiful piece of work. Raman was fascinated by fibrous gypsum and Jayaraman carried out X-ray diffraction studies on them to find the fibre axis. Along the length of the fibre, the bundles would transmit light freely but in the perpendicular direction there was hardly any transmission of light. This is similar to the modern fibre-optics transmission, except that it occurs in Nature! During this period, Jayaraman did his M.Sc. (by research) and Ph.D. based on the crystal optics work done with Raman, both the degrees being awarded by Madras University.

Raman was an increasingly lonely figure in the decade of the fifties. Jayaraman was one of the few scientific companions of that period, who took part, besides research, in many of the science-building activities of Raman. For example, he was actively involved with the Indian Academy of Sciences (IAS, Bangalore), having become a Fellow in 1955 at the young age of 29, after passing the Raman test (of scientific merit and the impact of one's contribution to scientific thinking in a particular area). For Raman, scientific promise was also important. He was prescient and bold in encouraging young scientists. Jayaraman was a member of the Council of the Academy and its treasurer from 1955 till 1960. He also served as the Chief Editor of *Current Science* during 1955–58, and played a key role in initiating the scrupulous and meticulous review process of submissions to the journal. His involvement with *Current*

Science continued; for example, in the nineties he published a couple of articles in the journal dealing with high-pressure phenomena in solids, and also organized a Special Issue on Gem Materials. Jayaraman remembered his mentor Raman in print in several ways: on the occasion of Raman's birth centenary, Jayaraman and A. K. Ramdas (Purdue University, USA) wrote an article on him in *Physics Today* (1988, **41**(8), 56–64). A full-length book entitled *C. V. Raman – A Memoir* by Jayaraman, was published in 1989 (Affiliated East West Press, New Delhi). This has been reissued by the IAS, in 2017.

Jayaraman left for USA in 1960 (it was not a happy parting) and worked with George Kennedy at the interdisciplinary Institute of Geophysics and Planetary Physics (University of California, Los Angeles, USA) there in high-pressure physics. This was a field completely new to him. He made important original contributions using the conventional piston cylinder method of generating high pressure. The comfortable upper limit for high pressure in the device was a relatively modest, less than 100 kbar, while even the opposed anvil cell equipment could generate pressure half a magnitude or more higher. Within this range, through imaginative and careful experimentation and technical development, Jayaraman discovered many qualitatively new phenomena, e.g. the first unambiguous evidence for the destruction of the covalent bond in compound semiconductors (the most famous example being Indium Antimonide (InSb)) and fusion curves of several metallic elements which showed evidence for electronic transitions.

In 1963, Jayaraman joined Bell Labs and worked there till 1990, when he retired as a Distinguished Member of the Technical Staff. This unique gift of a telephone company, to science and technology, had the world's leading figures in many areas working in close symbiosis (a Bell Labs motto was 'get the best people in the world and get out of the way'). In its golden period, Bell Labs was the Mecca for condensed matter physicists. The transistor had been discovered there and the field of semiconductor science was opening up. Jayaraman made significant contributions to our understanding of many semiconductor phenomena, e.g. the Gunn effect in Gallium Arsenide (GaAs). He developed the Teflon sleeve for high-pressure systems which enabled one to generate truly hydrostatic high pressure. This was crucial for the study of electrical resistivity in many materials which exhibited insulator-to-metal transitions, and contributed significantly to the birth and growth of this major field. An example is the classic metal–insulator transition in vanadium sesquioxide (V_2O_3), which was extensively studied in Bell Labs. In the same general field, Jayaraman discovered the semiconductor-to-metal transition in Samarium Sulphide (SmS) in which the black insulator turns into a gold-coloured metal; a visually compelling demonstration of this phenomenon. Its ubiquity in several rare-earth chalcogenides was realized by him and colleagues. The transition occurred at a remarkably low pressure of 0.65 GPa. The metallic state was recognized by him to be due to a transition to a different valence state of Sm (Sm^{2+} to Sm^{3+}). This discovery began the entire field of mixed valence, in which the ions of the solid material exist in a quantum mechanical admixture of two states of different integral valence. Jayaraman fondly recalled almost four decades later how the celebrated physicist P. W. Anderson (then also at Bell Labs) would bring visitors to his room to show this gold-to-black or metal-to-insulator transition. When a piece of doped SmS, which is metallic and golden in colour, is dropped suddenly into a flask containing liquid nitrogen, it immediately shatters into a black powder which upon warming becomes a golden-coloured powder! This field branched out into that of heavy fermions. Here one consequence of (mildly) mixed valence is the fact that the carrier electrons in the solid acquire a large effective mass; they become 'heavy', typically 50–100 times heavier than a free electron. Jayaraman's work involved materials, physics and instrumentation, and was greatly enhanced by the unique ecosystem of Bell Labs. Various well-characterized compounds, even the most difficult ones, could be synthesized; whole new areas of the new physics could be explored and sophisticated instrumentation could be fabricated. Informing all this was Jayaraman's mix of finesse in devising and carrying out experiments, recognizing and studying unexpected phenomena, a strong aesthetic sense and simple, deep ways of understanding. He was not shackled by disciplinary bonds; his work involved physics, chemistry, mineralogy and materials science. A long and fruitful career in Bell Labs saw him transition smoothly into the diamond anvil cell (DAC) era of high-pressure physics starting in the late 1960s. Jayaraman became a world leader in the exploitation of this compact and versatile device in which immensely high pressure (reaching several million times the atmospheric pressure) could be produced by two opposing diamond anvils bevelled to very small (~0.2 mm) flat surfaces between which the sample is placed. The discovery of the insulator–metal transition in SmS was an early use of the DAC. Jayaraman's review of the DAC techniques, describing both the instrumentation and physical systems studied, written in 1983, nearly 40 years ago, is a classic and the 'Bible' of the field.

Jayaraman was in the Hawaii Institute of Geophysics and Planetary Physics. University of Hawaii, Manoa from 1991 to 1996 and in the Carnegie Institution of Washington, DC for three years thereafter. He was in Florida till 2014, and later shared his time between Denver, Colorado and Phoenix, Arizona to be near his daughters.

Jayaraman had a strong and long association with Indian science. In the field of high-pressure physics, he was the inspiration for many groups and helped establish them. In 1971, just after the famous discovery of the black-to-gold, namely insulator-to-metal transition in SmS, he spent a year as a Guggenhein Fellow at the National Aeronautical Laboratory (NAL), Bangalore. True to his nature, he carried his equipment with him. He unpacked his bag containing a DAC and also the precious samples, and taught how to load them and pioneering X-ray crystallographic studies of rare-earth chalcogenides initiated with A. K. Singh and T. G. Ramesh got going. Just after his retirement from Bell labs, in 1990, he spent a year at the Indian Institute of Science, helping set up the high-pressure Raman spectroscopy studies there with A. K. Sood and his then Ph.D. students N. Chandrabhas and Victor S. Muthu. Usha Chandra from Department of Physics, University of Rajasthan, Jaipur spent a month at IISc, and started high-pressure Mössbauer work. Jayaraman spent a month as a visiting scientist at the National Geophysical Research Institute (NGRI), Hyderabad, initiating its Mineral Physics Division in 1991. Again in 1993, he spent a week at NGRI, helping high-pressure mineral physics studies take hold there. He also formed an enduring association with scientists at the Bhabha Atomic Research Centre, Mumbai, with those like B. K. Godwal benefitting immensely from the association. Jayaraman's annual visits to Chennai in December for the carnatic music season helped continue and strengthen his scientific connect. The connect continued

till very late in his life; as late as 2014, when he was nearly 90, he spent time with S. Arumugam and his group at the Centre for High Pressure Research, Bharatidasan University, Thiruchirappalli, and helped establish magnetic measurements at high pressures with a specially designed DAC (which he had brought with him).

Jayaraman was awarded the Krishnan Gold Medal of the Indian Geophysical Union in 1969, the Guggenheim Foundation Fellowship (which he held at the National Aeronautical Laboratory, Bangalore, India) in 1970, and the Alexander von Humboldt Fellowship in 1979–80 (which he held in Stuttgart, Germany). He was elected a Fellow of American Physical Society in 1969 and became a Distinguished Member of the Technical Staff of Bell Labs in the early 1980s.

Jayaraman was a great lover and lifelong student of classical (Carnatic) music, making his annual 'pilgrimage' to the concerts during the December music season in Chennai, as mentioned above. He was personally close to many of the legendary musicians of the time, some of whom stayed with him during their visits to USA. In his late eighties and nineties, when such annual visits were not possible, he bought access to the streamed concerts. He said in an e-mail to one of us, 'the new crop is excellent, their virtuosity and Sruti suddam are amazing. Some of them are switch overs from (being) High Techies to Carnatic Music'.

Jayaraman was a gentle, soft-spoken, nonaggressive, loveable person. He was a 'friend of all the world' as Kipling said of Kim, because of these traits of his personality and his wisdom, patience and concern for people. His steadfast, lifelong companion and wife Kamala was a great source of strength for him, as were his biological family of two daughters, grand and great-grand children, and also the extended family of friends and admirers. The passing away of this gentle giant is a great loss to the Indian scientific community.

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