K. S. Krishnan: Birth centenary

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K. S. Krishnan, an outstanding physicist as well as an erudite scholar in philosophy, has been a role model of a teacher – a *guru* – to a whole generation of Indian scientists. Calcutta, Dacca, Allahabad and Delhi had the privilege of having him as an intellectual star. He was a product of the golden age of Indian science in the twenties and thirties, a tradition which he maintained till the fifties.

Kariamanikkam Srinivasa Krishnan was born on 4 December 1898 in the village Watrap in the Tirunelveli (Ramnad) District of Tamil Nadu, the son of a school teacher. Afer schooling in Watrap and Srivilliputtur town, he studied in American College, Madurai, and Christian College, Madras, before accepting the post of a Demonstrator in Chemistry in the Christian College. In 1920, he went to work as a research scholar with C. V. Raman in the Indian Association for Cultivation of Sciences (IACS), then at 210 Bowbazar Street, Calcutta. In December 1928, he moved to the Dacca University as the Reader of Physics with S. N. Bose as the Head of the Department. In 1933, he came back to IACS, Calcutta as the Mahendra Lal Sircar Professor of Physics. In 1942, he was made the Professor and Head of the Department of Physics at the University of Allahabad. In 1947, Krishnan moved to Delhi to become the Director of the National Physical Laboratory. On 14 June 1961, he died after a heart attack.

The scientific work of Krishnan covered the investigations of the scattering of light by materials and the associated spectroscopic studies, the magnetic behaviour of crystals including the study of the relationship between the magnetic anisotropy and the atomic arrangements in the crystal lattice, electrical transport phenomena in solids, lattice dynamics and thermionic emission, the sequence being more or less in the chronological order. It is indeed remarkable that he made a significant mark in every one of these topics, a fact which invokes even greater admiration when we realize that Krishnan combined all these with deep love, scholarship and erudition in Indian philosophy, Tamil literature and Carnatic music right from his early childhood.

In the early 1920s, Raman started his studies of the scattering of light from various materials, having already made a mark by his work in accoustics, especially the behaviour of Indian musical instruments. The linkage with the work of the classic giants of acoustics like Rayleigh and Helmholtz made the group to study the intensity and the polarization of the light scattered by various molecules, slowly discovering facets which were not quite along the expected lines. The historic events of 28 February 1928 have been aptly summarized by K. R. Ramanathan, a ringside spectator and participant in the events. It appears that on that fateful day Krishnan had to attend some domestic ceremonies and came after lunch to the Association. The day happened to be a little cloudy. Raman, keen to carry on with the investigations, decided to use a mercury arc lamp which was the next brightest source. However unlike the white light of the sun, the mercury arc gives a few characteristic lines. Thus Raman decided to analyse the scattered

Hindu High School building where Krishnan began his career.

K. S. Krishnan (1898–1961).

Front and rear views of Krishnan's house in his native village Watrap in Tamil Nadu as it stands today.

light with the available spectrograph. When Krishnan came after lunch, he found the Professor excitedly arguing about the new radiation. Instead of the photometric measuring of the intensity of light scattering, the spectral analysis of the scattered light had revealed wavelength shifts. Krishnan quietly checked the observations and before the evening he had studied benzene and carbontetrachloride which were available as purified liquids. The analogy with the wavelength shifts observed in the Compton effect, which had been awarded the Nobel prize and was very much in the news, showed that there may be novel quantum effects quite different from the classical Rayleigh or Tyndall or Mie scatterings. The next few days, weeks and months were therefore periods of intense activity for Krishnan, Raman and others studying the various aspects of this new phenomenon. The publications during this period show all the excitement of these new explorations.

The saga of Raman effect, the inelastic scattering of light, has a special place in the development of quantum ideas of radiation. It showed Indian science at its best. The studies rapidly moved from the efforts to understand the full physics of the phenomenon to the application of this new knowledge as a tool to study various molecules, gases, liquids and solids. During this century, India has not perhaps succeeded in recapturing this leadership position. Some persons with a flair for the so-called investigative journalism have attempted to paint a picture that Krishnan had actually made the discovery and that Raman had taken the credit. Such uninformed mudslinging does great harm to both persons. No one goes up by pulling down others. Fortunately Raman and Krishnan had great mutual respect and affection, visiting each other fairly regularly.

Krishnan showing the new laboratories of NPL to Rajendra Prasad and S. S. Bhatnagar.

Krishnan used his innovative experimental skills to set up a new method of measuring the anisotropy of magnetic susceptibility in crystals. With modest facilities available at Dacca, he suspended the crystal by a quartz fibre in a uniform magnetic field. The anisotropy produces a torque which could be measured. The effect could be amplified by using liquids with a susceptibility equal to the mean value. This simple idea enabled him to perform a whole series of delicate magnetic measurements and relate them to the anisotropic atomic arrangements in crystals like graphite, benzene and naphthalene. The studies on rare earth and ferromagnetic salts gave the first integrated evidences for the crystal field theories. Schoenberg, who was a young scholar in the University of Cambridge, recalls how he was inspired by Krishnan's elegant exposition of this simple method and started to use it successfully to study the (de Htass–Van Alphen) magnetic susceptibility of metals at high fields and low temperatures. Schoenberg was later to visit National Physical Laboratory in the early fifties and set up a good group working on low temperature physics. These investigations of Krishnan, in light scattering and magnetic measurements, were considered so profound that he was elected to the Fellowship of the Royal Society, London in 1940 at a relatively young age of 42 years.

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a, Felicitation to Krishnan on his 60th birthday in December 1958 at NPL with the participation of Lal Bahadur Shastri, Jawaharlal Nehru, M. S. Thacker, D. S. Kothari and H. J. Bhabha. ***b***, Krishnan replying to the felicitations with his characteristic lecture posture.

The movement to Allahabad in 1942 produced another gem of a work from Krishnan, this time in theoretical ideas. Along with a young colleague A. B. Bhatia, Krishnan started to analyse the electrical behaviour of binary alloys, first in the framework of the Bragg–Williams approximation, and later of metallic liquids. In the analysis of the electron scattering processes responsible for the electrical resistivity, they introduced a new formalism of treating the potentials. Many years later the idea was popularized by Ziman in dealing with many molten metals and alloys and is called the Ziman formalism. Along with S. K. Roy, Krishnan also investigated the lattice dynamics of alkali halides and other systems, at a time when many aspects of the theory were not fully understood.

Moving to the National Physical Laboratory, New Delhi, Krishnan conceived of another ingenious idea to measure the thermionic emission constants. The equilibrium radiation in an enclosed cavity approaches the black body distribution and can be studied by having a small orifice through which the radiation leaks out. In an analogous fashion, the electron distribution in a heated cavity comes into equilibrium thermonic emission and could

Krishnan's photograph framed in his old house now occupied by his nephew.

be studied by allowing the electron stream to effuse through a small orifice. Along with S. C. Jain, a set of investigations were done to confirm these vapour pressure measurement ideas and to estimate the thermionic emission constants of several materials. Krishnan's versatility allowed him to solve a number of mathematical questions concerning the temperature distribution of such systems.

The collected works of K. S. Krishnan were edited by K. Lal and brought out by the National Physical Laboratory in 1988.

In his personal life, Krishnan was one who combined deep scholarship in many areas with high human values of ethics and justice. He was at the same time a model of humility and dignity, with no trace of arrogance. His mastery of Sanskrit and Tamil literature as well as Indian philosophies made him an unusually rounded personality. He loved tennis and bridge and could be quite witty in conversation. When he died, he left behind his wife, two sons and four daughters as well as numerous other colleagues to mourn the loss.

The scientific stature of Krishnan attracted numerous honours. The fellowships of almost all Indian Academies, and of several Academies/Societies abroad, the Knighthood of the British Government, the first Bhatnagar Memorial Award, the National Professorship at the age of 60 and numerous honorary doctorates rested lightly on his shoulders, making no difference to his humility and human qualities. In the late forties and fifties, he had to spend considerable time in working with the Council of Scientific and Industrial Research, University Grants Commission, Department of Atomic Energy and several other government agencies. All these he did along with his pursuit of science and culture.

He was perhaps a current day model of the ancient sages or rishis who made India great.

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K. S. Krishnan: A pioneer in condensed matter physics

T. V. Ramakrishnan

K. S. Krishnan was among the first to explore many interesting phenomena in the solid and liquid states of matter after the birth of quantum mechanics. He was very much at ease with the then new wave mechanics and used its ideas creatively and imaginatively. He developed apparently simple but ingenious experimental techniques for measuring solid state properties. He recognized and exploited connections between phenomena in different fields of physics. He was very perceptive in realizing the significance of many new and old observations concerning condensed matter, often presaging their formal elaboration by decades. It is specially necessary to recall these aspects now, when the prevailing ethos is one of often extreme specialization in form and content. I shall try to briefly summarize here some of Krishnan's contributions to condensed matter physics from the points of view mentioned above. Some of the areas to which he contributed are: molecular arrangement in solids and liquids using magnetic and optical anisotropies, electronic nature of graphite as reflected in its diamagnetism, the Jahn–Teller effect, the essential role of structural disorder-order in the electrical transport properties of elemental solid metals as well as alloys and liquid metals, and finally the determination of work function of metals[1].

In a series of papers extending over several years, Krishnan and his collaborators, first at Dacca and later in Calcutta, showed how the magnetic properties of many aromatic molecular crystals[2] and of inorganic complexes[3–6] reflect molecular anisotropies, bonding and crystal field effects. Clever techniques such as immersing the crystal in a fluid with the same average magnetic susceptibility so that the small residual crystalline anisotropies stand out and can be accurately measured, and new ways of measuring small torques even for tiny crystals, were some of the tools that enabled them to get the numbers needed. Krishnan and collaborators chose a number of homologous or closely related families. From the values of the diamagnetic susceptibility and its anisotropy, compared with crystal structural (X-ray) information, optical anisotropy, and molecular calculations, they sought to obtain quantitative measures of how different side groups or addition of benzene rings changes molecular size, shape, rigidity and orientation.

An equally impressive achievement is the work on paramagnetic ions in crystals, where using magnetic measurements, many of the crystal field theory-based ideas of van Vleck and coworkers are substantiated[3,4]. For example in $CuSO_4 \cdot 5H_2O$, from the size sign of magnetic anisotropy, the actual symmetry of the crystalline electric field as well as the rhombic deviation from cubric symmetry of this field, and the coincidence of crystalline field and magnetic axes are inferred[4]. The small room temperature deviation from Curie law ($\chi \propto T^{-1}$) for the magnetic susceptibility in Tutton salt, $MnSO_4 \cdot (NH_4)_2SO_4 \cdot 6H_2O$, is connected with the final temperature reached in its adiabatic demagnetization[5].

A study of nearly hundred rare earth and transition metal ion salts is used to 'map out' the systematics of crystalline electric fields at these ion sites as a function of electronic configuration and crystal structure[6].

This whole effort is remarkable for clarity of physical insight, the cogency of many different types of arguments used, the kinds of evidence marshalled, completeness, sustained effort and even lucid writing! This was one field where quantum mechanical wave function ideas were first applied successfully to crystals, and Krishnan was clearly an imaginative leader in giving substance to this enterprise.

A very interesting anomaly which Krishnan spotted is the diamagnetism of graphite[7]. The diamagnetic susceptibility is much larger for magnetic field perpendicular to the basal plane than for field along the plane, by a factor of forty