K. R. Rao – A remembrance (1936–2008)

K. R. Rao, Ex-Director, Solid State and Spectroscopy Group, BARC and Associate Editor, *Current Science*, died on 2nd December 2008 following cerebral haemorrhage two days earlier. I had met him in mid-October during my visit to Bangalore. He was distraught after the demise of his wife, Soni, a few months ago, but was coping with the tragedy. I was shocked to hear about his demise. We both were graduates of the first batch of the DAE Training School (1957–58), and this sad news brought in a number of messages from our batchmates describing Rao as polite, soft-spoken, gentle and caring, quiet and unassuming, and committed to scholarship and development of science in India.

I first saw Raghavendra Rao when he visited our home to meet my father who was the Head of the Physics Department at Banaras Hindu University (BHU), Varanasi. Rao had joined the M Sc course in 1955. I was doing B Sc during the same period (1955–57). He passed his M Sc in 1957 with a first rank.

In 1957 we both joined the first batch of the DAE Training School in Bombay. We were colleagues for the next 39 years and friends for 51 years. We lived for a year in the Training School hostel, which was located in the vacated Army barracks at Land's End, Bandra. His room-mate was N. Kameshwar Rao, his batch-mate from BHU days. We spent endless hours in his room with some of our batchmates. We would travel from Bandra to King's Circle on Sundays to have a proper South Indian meal – Mysore style.

On graduating from the Training School, Rao, Satya Murthy and I were chosen to join the Nuclear Physics Division to work with neutrons at Apsara Reactor. K. R. Rao joined V. P. Duggal, who was measuring cross-sections and N. S. Satya Murthy and myself joined P. K. Iyengar, who had initiated work towards starting neutron scattering from condensed matter. We occupied adjacent offices and our experiments were in the adjoining reactor hall; therefore, there was a lot of exchange of thoughts. I have also pleasant memories of the time we spent at the Mysore Association after office hours.

Rao's first task at work was to measure the neutron spectrum emerging out of a beam tube of the Apsara Reactor, using a single-crystal spectrometer. While it is expected that the spectrum emerging should be a smooth Maxwellian, Rao and Duggal found a number of sharp dips as a function of neutron energy. This was the first observation with neutrons of what is known to X-ray scientists as the Renninger Effect, the dips arising due to multiple Bragg reflections when one uses thick single-crystals.

In 1960, two years after joining the Nuclear Physics Division, Rao was chosen as a Colombo-Plan fellow to work at Chalk River Nuclear Laboratories with B. N. Brockhouse on the measurement of phonon dispersion curves. Walter Kohn had predicted that one should be able to see anomalies in phonon dispersion curves in metals having a strong electron–phonon coupling, at certain phonon wavelengths which have a defined relationship with the Fermi surface of the metal. Lead with a high superconducting transition temperature, suggesting a high electron–phonon coupling, was chosen as a test candidate. As the effect is small, measurements need to be accurate. Rao participated in these experiments and the first experimental observation of Kohn anomalies was theirs. Then Rao made careful measurements of intensities of phonons in germanium over a large region of reciprocal space with a view to determining the eigen-vectors of the phonons – a difficult experiment. He also participated in neutron-scattering measurements at Chalk River, on observing crystal field splitting in rare earth compounds and on liquid argon, with a view to determining its time-dependent self and pair correlation functions. Rao and I worked together on the latter experiment and co-authored a paper. During the period in Chalk River, there were a number of Indians from BARC (and also some other laboratories) who were put up on the same floor at the New Staff Hotel. This made it easy for us to have joint cooking programmes with distinct responsibilities handed over to different persons. Rao would usually volunteer to wash the vessels. On weekends, we would often spend time in his room, discussing all kinds of topics with great passion and vigour. One could see the passionate side of Rao, who was normally quiet and soft spoken, in these meetings. The discussions always ended with a cup of coffee, about which Rao was very particular, as he would not get sleep without it. Rao returned to India in 1962.

I remember discussing with him about what he would be doing on his return to India. He wanted to build a triple-axis spectrometer on his own, but was somewhat apprehensive whether this would be acceptable to Iyengar (as Duggal, his senior colleague, had left by then for Delhi). I encouraged him to discuss the matter with Iyengar. Indeed, after his return to India, Rao built a triple-axis spectrometer with paper-tape automation as against relay-based automation of earlier spectrometers at Trombay. His first experiment with this machine was diffraction from liquid CCl_4, where Rao could separate the inter- and intramolecular parts in the diffraction pattern. Several inelastic scattering experiments were done using this triple-axis spectrometer over two decades. We collaborated on neutron inelastic scattering work on liquid CH_4 and CD_4 during this time. Rao also worked on phonons in metals, especially in zinc, where he and his colleagues were able to observe the distinct signature of Kohn anomalies even at room temperature and relate it to the Fermi surface of Zn.

In a sabbatical year, 1969–70, at the Army Materials and Mechanics Research Center, USA, Rao worked on the group theory and lattice dynamics of potassium and sodium azides which are explosives. This work got Rao and his co-workers

the Paul Siple Award (1971) of the Army, as also a commendation for technical writing – an ability quite visible in his contributions to *Current Science*.

On returning to India, Rao started to look at phonons in 'molecular' ionic solids, e.g. KNO_3. In systems with increasing number of atoms per primitive unit cell, the number of phonon branches increases and the experiments become more difficult due to lack of neutron intensity. Nevertheless, Rao pushed successfully into this area with tenacity – perseverance was another quality of Rao. To be able to do these experiments intelligently, Rao developed necessary theoretical framework and computer programs to find out the regions of the reciprocal space where intensities would be favourable. These calculations needed a sensible lattice dynamical model and he chose to use the so-called rigid molecular-ion model for the purpose. The generalization of this programme to all kinds of complicated structures formed the basis of his long-term plan of action for studying lattice dynamics in geologically important (e.g. Mg_2SiO_4) materials. This led Rao and his group (Chaplot, Narayani, Mala and Mittal) to perform collaborative experiments in a number of high-intensity neutron sources around the world to measure phonon dispersion curves and frequency distribution functions and predict thermodynamic properties. This was highly appreciated internationally, as it gave important insight into (phase) changes occurring in geological materials as a function of temperature and pressure. This programme was also used to try to derive a universal set of potentials for each element which could be used for any compound. Measurements were also made in a number of other compounds, including high-temperature superconductors, etc. Rao also initiated computer simulation studies of the atomic dynamics of a number of solids, partly with a view to examining non-harmonic movements of atoms, for example, in palladium deuteride among others.

In 1972, BARC announced plans to build the high-flux Dhruva reactor. A whole new set of opportunities would become available to the neutron scattering group, as it could now consider better designed beam tubes and spectrometers. A set of about a dozen spectrometers was conceived along with special beam-tailoring devices. All of this was to be locally designed for optimizing intensity and resolution. This was an important challenge, as over the next several years newer designs had to be tested and implemented. Rao played a substantial role in this major team effort consisting of more than a dozen scientists and technical personnel. In this short write-up I will not be able to do justice to his personal contributions to the instrumentation development for Dhruva neutron utilization. However, I should mention at least a few – the neutron guide tubes for cold neutrons with Madhav Rao, modular design for spectrometers and data acquisition systems with P. R. Vijayaraghavan and spin-echo spectrometer with S. L. Chaplot.

When the Dhruva reactor became available we put in major efforts towards making these spectrometers available to all universities through the Inter University Consortium for DAE Facilities and by the time of Rao's retirement in 1996, more than thirty university groups were performing experiments at Dhruva. This was another very satisfying period of working together. I also remember organizing the International Neutron Scattering Conference, NS-91, Mumbai, where we both worked closely together as Convener and Secretary. Quiet efficiency, which was the hallmark of Raghavendra Rao, was fully visible at this time and just in spite of the first Iraq war at the time of the meeting, and visitors apprehensive of travelling East, the Conference turned out to be a resounding success.

Rao became Head, Solid State Physics Division, BARC in 1990 and Director, Solid State and Spectroscopy Group in April 1996, from which position he retired later the same year. He was elected Fellow of the Indian Academy of Sciences in 1986 and Indian National Science Academy in 1989. After retirement, Rao moved to Bangalore and soon after was persuaded to take up the role of an Associate Editor of *Current Science*, which he did with dedication and distinction; his balanced write-up in *Current Science* on the issues involved in the Indo-US nuclear deal, was an excellent example of his clarity on the subject and his ability to express it in simple and clear terms.

Raghavendra Rao and Soni were good friends of ours. Soni was a perfect companion and strength to Raghavendra, and he found it extremely difficult to bear her loss. We will miss them both and I express this sentiment on behalf of all our colleagues and friends.

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