Prof. Chintamani N.R. Rao
Albert Einstein Research Professor

Most important awards, prizes and academies

Among the various medals, honours and awards received by him, mention must be made of the Marlow Medal of the Faraday Society (1967), Bhatnagar Prize (1968), Jawaharlal Nehru Fellowship (1973), Padma Shri (1974), Centennial Foreign Fellowship of the American Chemical Society (1976), Royal Society of Chemistry (London) Medal (1981), Padma Vibhushan (1985), Honorary Fellowship of the Royal Society of Chemistry, London (1989), Hevrovsky Gold Medal of the Czechoslovak Academy (1989), Blackett Lectureship of the Royal Society (1991), Einstein Gold Medal of UNESCO (1996), Linnett Professorship of the University of Cambridge (1998), Centenary Medal of the Royal Society of Chemistry, London (2000), the Hughes Medal of the Royal Society, London, for original discovery in physical sciences (2000), Karnataka Ratna (2001) by the Karnataka Government, the Order of Scientific Merit (Grand-Cross) from the President of Brazil (2002), Gauss Professorship of Germany (2003) and the Somiya Award of the International Union of Materials Research (2004).

He is the first recipient of the India Science Award by the Government of India (2005). Rao received the million-dollar Dan David Prize for Science in the Future Dimension for his research in Materials Science. He was named Chemical Pioneer by the American Institute of Chemists (2005), Chevalier de la Légion d'Honneur by the President of the French Republic (2005) and received the Honorary Fellowship of the Institute of Physics, London (2006) and Honorary Fellowship of St.

Catherine's College, Oxford (2007). He received the Nikkei Asia Prize for Science, Technology and Innovation (2008). He was awarded the Royal Medal by the Royal Society (2009) and the August-Wilhelm-von-Hoffmann Medal for his outstanding contributions to chemistry by the German Chemical Society (2010). He received the Ernesto Illy Trieste Science Prize for materials research in (2011).

Prof. Rao was Albert Einstein Professor of the Chinese Academy of Sciences in 2012. The President of India conferred the title Bharat Ratna in 2014. The Emperor of Japan bestowed the Order of the Rising Sun, Gold and Silver Star in 2015. He was conferred the highest award for materials research, the von Hippel award by the Materials Research Society, in 2017. He is the first Asian to receive this award. The Centre for Advanced Materials of Ras Al Khaima has conferred the First Sheikh Saud International Prize for Materials Research (2019).

Summary of scientific research

C.N.R. Rao had just joined college after high school studies when India gained freedom in 1947. After his undergraduate studies in Bangalore, he obtained a Master of Science degree from Banaras Hindu University. He obtained the Ph.D. degree in chemical physics from Purdue University and carried out postdoctoral research work in the University of California, Berkeley. He returned to India in 1959 as a young faculty member at the Indian Institute of Science, Bangalore, which is the oldest and the most well-known research institute of India. Four years later, he moved to the new Indian Institute of Technology (IIT), Kanpur where he soon became head of the chemistry department. Rao's early research was mainly on spectroscopy and molecular structure. Rao's first book on *Ultraviolet and Visible Spectroscopy* got published from London in 1960 and his second book on *Infrared Spectroscopy* from the US in 1963. He slowly started working on solid state and materials chemistry, his earliest paper in this area being in 1958. He faced immense difficulties in starting research in India during those years, because of financial constraints and limited experimental facilities. However, some of his papers from 1960 are still being cited. Rao slowly built facilities for research in solid state and materials chemistry in IIT Kanpur and started research on metal oxides which constitute the largest family of materials with the widest range of properties. There were very few practitioners of solid state chemistry at that time. His one-year stay in Oxford as a Visiting Commonwealth Professor during 1973-74 made him realize the need to build a dedicated, well-equipped laboratory for solid state and materials chemistry which would compare favourably with laboratories in the advanced countries. With this purpose, after 14 years in IIT Kanpur, he returned back to the Indian Institute of Science to build new departments devoted to solid state chemistry and also materials science. He succeeded in building good facilities for research by the late 1970s. In his effort to build a major research programme in solid state and materials chemistry, he was inspired by his association with Prof. J.S. Anderson and Prof. Nevill Mott.

He was director of the Indian Institute of Science during 1984-94. The Government of India decided to establish Jawaharlal Nehru Centre for Advanced Scientific Research (JNCASR) in 1989 to celebrate the birth centenary of India's first Prime Minister with Rao as the founding president. JNCASR has emerged to be one of India's premier research institutions and Rao was

President of the Centre till 1999. He continues to work there as Linus Pauling Professor and honorary president. One of the main areas of research at JNCASR is chemistry and physics of materials.

Rao has been publishing extensively on a variety of aspects of chemistry of materials including novel methods of synthesis, discovery of new materials, tailor-making materials with desired properties and so on, for over half a century. He has worked on high-temperature superconductivity, colossal magneto-resistance, multiferroics and open-framework materials. In the last 20 years, he has been investigating various nanomaterials, specially nanotubes, nanowires and graphene.

As of today, Rao has published around 1770 research papers and 53 books. He has around 121,777 citations with an H-index of 157 and i10-index 1331. C.N.R. Rao is on the editorial boards of several journals dealing with chemistry, chemical physics, materials science and solid state chemistry.

Rao feels that the most enjoyable aspect of his career has been working with young students. Over 150 persons have received Ph.D. degrees working with him. Besides young coworkers and post-doctoral fellows, Rao has collaborated widely with scientists in Europe and the US. In the last 15 years, Rao has been making considerable effort to bring out science education materials (books, CDs etc.) for school children. He regularly delivers lectures to children in various parts of India.

Prof. Rao is proud that he spent his entire professional life of over 65 years in India. While it was difficult to do research at the frontier during the early years of his career, he feels happy that he has been able to accomplish whatever he could and to witness India transforming slowly from a very poor country to an emerging economy. It has also been a pleasure to grow with the subject of his research which was at its infancy when he started working in the 1950s.

Main publications

Some of the important contributions of C.N.R. Rao to materials research with key references to his work:

1. New Methods of synthesis of metal oxides and other inorganic materials. *J. Mater. Res.* (1986), *Acc. Chem. Res*. (1987), *Mat. Sci. Engg. B* (1993).

2. First synthesis of the liquid-nitrogen cuprate superconductor and related contributions. *Nature* (1987), *Phil. Trans. Royal Soc*. (London) (1991).

3. Colossal magnetoresistance in manganites and related effects. *Phys. Rev. B* (1996), *Adv. Mater.* (1997), *Chem. Mater*. (1998), *J. Phys. Chem.* (2000).

4. Metal-insulator transitions in metal oxides, and marginally metallic systems. *J. Phys. Chem*. (1995), *Chem. Commun*. (1996), *Solid State Phys*. (1999).

5. Large-scale electronic phase separation in metal oxides. *Chem. Mater.* (1999), *Phil. Trans. Royal Soc*. (Lond) (2008).

6. Precursor synthesis of carbon nanotubes, and generation of junction nanotubes and doped nanotubes. *Appl. Phys. Lett.* (1996, *Acc. Chem. Res.* (2002), *ACS*

Nano (2007), *Nanoscale* (2010).
7. Building inorganic frameworks and molecule-material transformations. *Acc. Chem. Res*. (2001, 2004), *Chem. Commun*. (2006).
8. New synthesis of inorganic nanomaterials and the use of the liquid-liquid interface for the purpose. *J. Colloid Interf. Sci.* (2005), *Dalton Trans*. (2007), *Acc. Chem. Res.* (2008).
9. New routes to multiferroics. *J. Mater. Chem*. (2007).
10. Separation of semiconducting and metallic carbon nanotubes. *Nano Research* (2009), *J. Am. Chem. Soc.* (2010).
11. Novel synthesis and properties of graphene, chemical doping of graphene and molecular charge-transfer with graphene. *Adv. Mater*. (2009), *Angew. Chem. Int. Ed.* (2009), *Materials Today* (2010).
12. Universal ferromagnetism in all inorganic nanoparticles. *Nanotoday* (2009).
13. Chemical storage of hydrogen in graphene, Synergy in mechanical properties of composites containing two-nanocarbons and IR detectors based on graphene. *PNAS* (2009), *PNAS* (2011), *Adv. Mater.* (2011).
14. Late, D.J., Liu, B., Matte, H.S.S.R., Dravid, P. and Rao, C.N.R. Rapid characterization of Ultra thin Layers of MoS2, GaS and GaSe on SiO2/Si Substrates, *Adv. Funct. Mater.* 22, 1894 (2012).
15. Late, D.J., Liu, B., Luo, J., Yan, A., Matte, H.S.S.R., Grayson, M., Dravid, V.P. and Rao, C.N.R., GaS and GaSe ultra thin layer transistors, *Adv. Mater.* 24, 3549 (2012).
16. Late, D., Huang, Y.K., Liu, B., Acharya, J., Shirodkar, S., Luo, J., Yan, A., Charles, D., Waghmare, U.V., Dravid, V. and Rao, C.N.R. Sensing behavior of atomically thin-layered MoS2 transistors, *ACS Nano*, 7, 4879 (2013).
17. Maitra, U., Gupta, U., De, M., Datta, R., Govindaraj, A. and Rao, C.N.R. Highly effective visible-light induced H2 generation by single-layer IT-MoS2 and a nanocomposite of few layer 2H-MoS2 with heavily nitrogenated graphene, *Angew. Chem. Int. Ed.* 52, 13057 (2013).
18. Dey, S., Govindaraj, A., Biswas, K. and Rao, C.N.R. Luminescence properties of B- and N-doped graphene quantum dots prepared from arc-discharge generated doped graphenes, *Chem. Phys. Lett*. 595-596, 203 (2014).
19. Gupta, U., Naidu, B.S., Maitra, U., Singh, A., Shirodkar, A.N., Waghmare, U.V. and Rao, C.N.R. Characterization of few-layer IT-MoSe2 and its superior performance in visible-light induced hydrogen evolution reaction, *Appl. Phys. Lett. (Mater)*. 2, 092802 (2014).
20. Late, D., Shirodkar, S.N., Waghmare, U.V., Dravid, V.P. and Rao, C.N.R. Thermal expansion, anharmonicity and temperature-dependent Raman spectra of single- and few-layer MoSe2 and WSe2, *Chem. Phys. Chem*. 15, 1592 (2014).
21. Gopalakrishnan, K., Sultan, S., Govindaraj, A. and Rao, C.N.R. Supercapacitors based on composites of PANI with nanosheets of N-doped RGO, BC1.5N, MoS2 and WSe2, *Nanoenergy* 12, 52 (2015).
22. Chhetri, M., Maitra, S., Chakraborty, H., Waghmare, U.V and Rao, C.N.R. Superior performance of borocarbonitrides, BxCyNz, as stable, low-cost metal-free electrocatalysts for the hydrogen evolution reaction, *Energy Environ. Sci. (Commun.)* 9, 95 (2016).
23. Kumar, R., Raut, D., Ramamurthy, U. and Rao, C.N.R., Remarkable Improvement in the

mechanical properties and CO2 uptake of MOFs brought about by covalent linking to graphene, *Angew. Chem. Int. Ed*. 55, 7857 (2016).
24. Pramoda, K., Gupta, U., Ahmad, I., Kumar, R. and Rao, C.N.R., Assemblies of covalently cross-linked nanosheets of MoS2 and of MoS2 – RGO: Synthesis and novel properties, *J. Mater. Chem*. A4, 8989 (2016).
25. Chhetri, M., Sultan, S. and Rao, C.N.R. Electrocatalytic HER activity comparable to platinum exhibited by Ni/Ni (OH)2/graphite electrode, *PNAS*, 114, 8986 (2017).
26. Rajamathi, C.R., Gupta, U., Kumar, N., Yang, H., Sun, Y., Süß, V., Chandra Shekhar, B., Schmidt, M., Blumtritt, H., Werner, P., Yan, B., Parkin, S., Felser, C. and Rao, C.N.R. Weyl semimetals as catalysts,*Adv. Mater.* 29, 1606202 (2017).
27. Vishnoi, P., Mazumdar, M., Pati., S.K. and Rao, C.N.R., Arsene nanosheets and nanodots, *New J. Chem. (Letter)*, 42, 14091-14095, 2018.
28. Sreedhara, M.B., Gope, S., Vishal, B., Datta, Bhattacharyya, A.J. and Rao, C.N.R., Atomic layer deposition of crystalline epitaxial MoS2 nanowall networks exhibiting superior performance in thin-film rechargeable Na-ion batteries, *J. Mater. Chem. A. 6*, 2302 (2018).
29. Roy, A. Singh, S.A. Aravindh, S. Servottam, U.V. Waghmare, C.N.R. Rao, Structural Features and HER activity of Cadmium Phosphohalides, *Angewandte Chemie*, 131 (21), 7000-7005, (2019).
30. P. Vishnoi, K. Pramoda, U. Gupta, M. Chhetri, R.G. Balakrishna, C.N.R. Rao, Covalently Linked Heterostructures of Phosphorene with MoS2/MoSe2 and their Remarkable HER Activity, *ACS Applied Materials & Interfaces*, 11 (31), 27780-27787, (2019).
31. C.N.R. Rao, K. Pramoda, A. Saraswat, R. Singh, P. Vishnoi, N. Sagar, A. Hezam, Superlattices of covalently cross-linked 2D materials for the hydrogen evolution reaction, *APL Materials*, 8 (2), 020902 (2020).
32. Roy, A. Singh, S.A. Aravindh, S. Servottam, U.V. Waghmare, C.N.R. Rao, Effect of Mn2+ substitution on the structure, properties and HER activity of cadmium phosphochlorides, *RSC Advances*, 10 (9), (2020).

Some of the books on materials written or edited by C.N.R. Rao:

1. *Modern aspects of Solid State Chemistry*, Plenum Press (1970).
2. *Phase Transitions in Solids*, McGraw-Hill (1978).
3. *Preparation and Characterization of Materials*, Academic Press (1981).
4. *New Directions in Solid State Chemistry*, Cambridge University Press (1986, 1997).
5. *Superconductivity Today*, Universities Press (1992).
6. *Chemistry of Advanced Materials*, Blackwell (1992).
7. *Chemical Approaches to the Synthesis of Inorganic Materials*, John Wiley (1994).
8. *Metal-Insulator Transitions Revisited*, Taylor & Francis (1995).
9. *Transition Metal Oxides*, Wiley-VCH (1995).
10. *Colossal Magnetoresistance and related phenomena*, World Scientific (1998).
11. *Nanotubes and Nanowires*, Royal Soc. Of Chemistry, (2005, 2011).
12. *Nanochemistry*, Wiley-VCH (2007).

13. *Graphene and its fascinating properties*, World Scientific (2011).
14. *Essentials of Inorganic Materials Synthesis, C.N.R. Rao and K. Biswas, John Wiley,* New York, 2015.
15. *2D Materials beyond Graphene, C.N.R. Rao and U.V. Waghmare (Eds), World Scientific*, 2017.
16. *Advances in the Chemistry and Physics of Materials – Overview of Selected Topics, Subi J George, Chandrabhas Narayana and C.N.R. Rao (Eds.), World Scientific, 2019.*