B. M. Udgaonkar (1927–2014)

The tradition of particle physics was started in India by Homi Bhabha in the early forties, and was continued into the fifties by him along with his experimentalist colleague M. G. K. Menon. B. M. Udgaonkar played a pivotal role in carrying forward this tradition into the sixties along with Virendra Singh. Although Udgaonkar was working in the DAE/TIFR establishment at the Old Yatch Club during the fifties, much of this period was devoted by him to the study of nuclear reactor theory. He was sent by Bhabha to the French Atomic Energy Centre in Saclay for a year and half to gain expertise in theoretical reactor physics, which he used to build up a group in that area on his return. This group eventually moved to Trombay as the theoretical physics group of BARC. Nonetheless, he wrote several significant papers in particle physics during the fifties. However, the glorious period of Udgaonkar's research career in particle physics came in the early sixties, when he spent two years in the University of California, Berkeley, followed by a year in the Institute of Advanced Study, Princeton.

Udgaonkar was visiting the group of Geoffrey Chew at Berkeley during 1960–62, where Virendra Singh had gone as a Ph D student. This was the era of hadron physics. Hadron is a collective name for both types of strongly interacting particles, mesons and baryons, having integral and half-integral spins respectively. The lightest meson and baryon are the pion, π and the nucleon, N. Several dozen of mesons and baryons with various masses and spins had been discovered mainly at the Bevatron accelerator at Berkeley. It was clearly not tenable to describe them all as fundamental particles. Nor was it possible to describe a few as the fundamental ones, of which the others would be composite states. Even the mass hierarchy was not relevant, since for strong interactions the binding energy can be as large as the rest mass energy, so that a relatively light particle can be a bound state of two heavy ones. This led to a new paradigm, which their mentor and the leader of the Berkeley group, Chew, called 'particle democracy'. That means there is no distinction among constituent, composite and exchange particles (careers of the strong nuclear force). Each hadron plays all the three roles. Thus in contrast to atomic or nuclear physics, where one uses the masses of the constituent and the exchange particles along with their couplings to compute the masses and couplings of the composite states, one can determine here all these masses and couplings in terms of one another using a set of consistency conditions. This was called the 'bootstrap principle'. Of course, one had to pay a big price for dealing with strong interaction physics, since one can no longer use the standard perturbative techniques of quantum mechanics. Instead one has to work out the strong interaction dynamics using the dispersion relation, based on the general properties of analyticity and crossing symmetry of the scattering amplitude (S-matrix) in the squared energy and four-momentum transfers – s, t and u. For identical particle scattering they can be simply expressed in terms of the common mass m, momentum q, and scattering angle θ in the centre of momentum frame, i.e.

$$s = 4(q^2 + m^2),\ t = -2q^2(1 - \cos\theta),$$
$$u = -2q^2(1 + \cos\theta).$$

Moreover, one had to make some simplifying approximations, like approximating the low-energy scattering amplitude by the light particle exchange forces in the t and u channels. In particular, the $\pi^+\pi^- \rightarrow \pi^+\pi^-$ scattering amplitude provides a simple example, where the mass and coupling (width) of the ρ meson resonance in the s-channel can be determined together with those of the ρ meson exchange in the t channel using the self-consistency conditions (bootstrap principle).

Udgaonkar and Virendra Singh wrote three papers in the *Physical Review* during 1961, 62 and 63 using the above-mentioned dispersion relation to determine the low energy $\pi N \rightarrow \pi N$ scattering amplitude. In particular, the third paper determined the mass and width of the Δ baryon resonance in the s-channel along with those of the Δ baryon exchange in the u-channel using the bootstrap principle, where they had to use the mass and couplings of the ρ meson in the t-channel as experimental inputs. This paper earned them international recognition in particle physics.

Around the same time Udgaonkar wrote a pioneering paper in the *Physical Review Letters*, describing the high-energy scattering cross-sections of hadrons by Regge poles. This was quickly followed by his second paper on Regge poles with Murray Gell-Mann (later Nobel laureate) and a third one with N. N. Khuri, all in the *Physical Review Letters*. The last one was written from the Institute of Advanced Study, Princeton. He also gave a lecture course on the phenomenology of Regge poles at the famous Scottish Universities' Summer School in 1963.

What are Regge poles? We see from the above kinematic equations that in two-body scattering the squared four-momentum transfers t and u are negative, which means by energy–momentum conservation the exchanged particles in these channels must have negative mass-square, i.e. imaginary mass. This is evidently not possible in classical mechanics. But thanks to the uncertainty principle, the energy–momentum conservation can be temporarily suspended to allow the exchange of particles with positive mass-square (real mass) in quantum mechanics. Quantum field theory gives an equivalent prescription, preserving energy–momentum conservation but changing the mass-square of the exchanged particle from positive to negative values, which is called its virtual mass. The spin of the exchanged fundamental particles like photon or electron, however, remains unchanged in the process. In contrast, we know from atomic and nuclear physics that the spin of composite state increases with its mass. The same should hold for hadrons. So the spin of the exchanged hadron goes down continuously with its virtual mass-square. This object of simultaneously varying spin and mass-square is called Regge pole. The Regge poles provide a simple and predictive model for the soft scattering region of hadrons at high energy, i.e. the near-forward (backward) scattering region, where the relevant four-momentum transfer square $t(u)$ remains small. Indeed, it remains a useful model for this purpose even now, because the present QCD (quantum chromodynamics) theory of hadrons as composite states of quarks and gluons becomes nonperturbative in the soft scattering region and hence has little predictive power here. On the other hand, the perturbative QCD technique has proved most useful in studying the hard scattering region of hadrons, corresponding to high energy and scattering angle, in terms of the constituent quarks and gluons.

When I joined Udgaonkar as a Ph D student in 1964, I had already published a paper on the dispersion relation analysis of a meson–nucleon (KN) scattering amplitude. But he explained to me that this is a well-explored technique, whose merits and limitations are pretty clear by now. So he suggested me to work instead on Regge pole model, which was still relatively new and hence potentially more interesting. But after having suggested this field, he left it entirely to my own devices to explore it to find suitable problems and their solutions. However, he used to sit down with me to go through the drafts meticulously to check the results and help me in improving their presentation, highlighting the main points with precision and clarity (without ever consenting to put his name as co-author, of course). I am indebted to him on four counts. First, Regge poles remained a thrust area of particle physics till the mid-seventies. Secondly, independence in research gave me confidence to enter the new era of particle physics in terms of the above-mentioned quarks and gluons, which took over the field thereafter. Thirdly, the presentation skills I learned from him were essential for making global impact in an intensely competitive field like particle physics, particularly from a remote place like India. Last but not the least important, the lesson I learned from him was to readily give to your younger researchers the benefit of your experience and expertise, while maintaining a strict code for co-authorship.

Udgaonkar had a multidimensional personality, of which I have only described one – like one of those seven blind men who went to see the elephant. Let me conclude with one reflection. In a wider sense Udgaonkar has been a teacher to many of us spanning many age groups and disciplines. If we live by the lessons we learned from him and pass them on to the younger generations through our deeds, that will be the best tribute we can pay to his memory.

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B. M. Udgaonkar's remarkable career in physics, particularly in particle physics, has been described by D. P. Roy. His equally remarkable career in science education began around the late nineteen sixties. I was a Research Scholar in the TIFR Theory Group during 1964–69 and his pedagogic ability as well as interest in educational and social issues were apparent to me while he mentored me in research. Soon he and some of his distinguished colleagues at TIFR felt motivated to look beyond the Institute and interact closely with the educational system outside. They started regular meetings with the municipal school teachers in Mumbai; lectured them informally to enrich their content knowledge, helped them develop innovative demonstrations and experiments, and also undertook to write materials. The activities gained considerable momentum in a few years and it was felt necessary to put them in an institutional framework. Thus was established under the leadership of Udgaonkar and his close colleague V. G. Kulkarni, the Homi Bhabha Centre for Science Education (HBCSE) in 1974 as a unit of TIFR. Another noteworthy offshoot of similar activities at TIFR at that time was the formation of the Bombay Association of Science Education (BASE) which continues to carry out valuable educational activity in Mumbai.

Udgaonkar was, of course, always concerned about science education at the tertiary (college/university) level. He took much interest in the academic affairs of University of Mumbai and encouraged and supported the University to establish its Department of Physics in 1971, headed by another TIFR colleague M. C. Joshi. In the same year was formed the Indian Physics Association (IPA), of which he was the founder President. He wrote extensively on university science education; his editorials in IPA's bulletin *Physics News* were noted for their perceptiveness and breadth. He was a member of the University Grants Commission (UGC) from January 1973 for three years, and was responsible for several UGC initiatives for improvement of science education in colleges and universities in the 1970s. His efforts led to the establishment of the Western Regional Instrumentation Centre (WRIC) at the University of Mumbai. Besides his honours and recognition in science, he had already by 1970s made a mark on the national scene in the education sector. He received the Hari Om Trust Award of the UGC for work at the interface of science and society in 1985; and the Padma Bhushan in 1985. He was widely regarded the 'conscience keeper' of the scientific community in India.

It was characteristic of Udgaonkar that he did not let his status as an eminent scientist and educationist, come in the way of direct contact with the stakeholders in education. He was approachable to everyone; students and teachers from the city and elsewhere freely turned to him for advice on their problems and even grievances. As early as 1968, he and his colleague Yashpal started weekly discussion sessions at TIFR for local college undergraduates on 'Feynman Lectures in Physics'. A few other TIFR colleagues including some Ph D students were also part of the effort. Several meritorious students of Mumbai colleges were drawn to this Study Group; many of them are now accomplished scientists in India and abroad. His passion for teaching showed up again when his initiative led to the TIFR–Pune University collaborative M Sc programme in physics, though for reasons beyond his control, it could not be sustained for long.

Udgaonkar was truly a man of many parts. Besides science and education, he engaged deeply with the issues surrounding global disarmament, security and peace for almost three decades. He was an early entrant of the Pugwash Movement and a member of the Pugwash Executive Council (1987–97). In this capacity he firmly put forward his nuanced views on these delicate and complex issues and explicated our country's concerns and viewpoint. The Pugwash led by Joseph Rotblat received the Nobel Prize for Peace in 1995.