India's physics experience

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The twentieth century saw revolutionary developments in the physical sciences. Its consequences for economic and lifestyle change are reverberating across the world, starting from its North. While life sciences are the obvious centres of attention in the beginning of this century, physics continues to be vital in science and technology and there is active engagement with questions such as its future and indeed of science itself. In this article, while I do not touch upon the last question, which is the most difficult and significant, I will recount the Indian Physics experience of the last century. Some features of the present state are pointed out, and a few suggestions for change made. This essay is clearly a personal view.

The emphasis of India's comprehensive intellectual culture was broadly linguistic, philosophical and literary. However, thinking about the physical world, inventing mathematical ideas and languages, and experimentation and technology, all have ancient roots. I mention one example of each of the above, because consciously or not, this is one of the formative influences of contemporary Indian activity in physics. The atomic theory was hypothesized by Kaṅāda (6th century BC) who, along with Praśastapāda, was the founder of the philosophical school called *Nyāya Vaiśeshika* or Logical Atomism. Their argument for the particulate nature of matter was the manifest inequality of different bits of it; if matter were infinitely divisible, how could a mustard seed be unequal to the Meru mountain? The philosophers of this school went on to describe diatomic and triatomic molecules formed of elementary atoms, thermal dissociation of molecules, and shape and size of atoms. The Kerala school of mathematicians, starting with Madhava in the 14th century, discovered and used differential and integral calculus in the course of expressing trigonometric functions as infinite power series, obtaining the famous series of Gregory, Newton and Leibniz and thence a value of π accurate to 11 decimals, all this two to three centuries before Newton and Leibniz. The famous Bulat or Damascus steels, prized by sword-wielding crusaders, are well known to have come from India, where the process of making wootz or ultrahigh carbon steel with the desired microstructure was highly developed. The fertile coming together of these three kinds of activity, a hallmark of contemporary science, did not happen and it was with the British conquest of India that science as we know it today entered the country. Some of the early landmarks of scientific discovery in India are directly connected with British rule, e.g. the discovery of gravity anomalies in the Himalayas by officers of the Trigonometrical Survey of India in the 1860s and its implications for the structure of the earth, and the discovery (in the 1890s) by Sir Ronald Ross of the Indian Medical Service that anopheles mosquitoes carry malaria.

Western higher education began to be officially sponsored and supported from the early 19th century, largely following Macaulay's 1835 Minute on Indian Education, which said that 'we must at present do our best to form a class who may be interpreters between us and the millions we govern; a class of persons, Indian in blood and colour, but English in taste, in morals, in opinions and in intellect', and argued 'for promotion of a knowledge of the sciences through English education'. For example, the Hindu College (1817, Calcutta; Presidency College since 1855) and the three universities of Calcutta, Bombay, and Madras (1855) date from this period. Towards the end of the 19th century and the beginning of the 20th, three factors, namely the results of this policy, resurgent national as well as cultural consciousness, and the revolution in physics came together to create the most remarkable period in modern Indian science. The best known figures of this period are icons in the contemporary national imagination; together they gave India a special position in the physics world. I will briefly describe their work and influence here, both for its own interest and because this is the immediate background for physics in India.

The first, and in many ways the most unusual, was Jagadish Chandra Bose (1858–1937), a pioneer in experimental studies of ultra-short (millimetre wavelength) electromagnetic waves, namely microwaves, and in the physical response of plants to stimuli. He went to study medicine in London in 1880, shifted to science at Cambridge and returned to teach at Presidency College. Here, in the 1890s, he started experiments on microwaves, generating and detecting them over distances of order a mile, a year or more before Marconi's experiments on longer wavelength radio waves. He established their identity as transverse electromagnetic waves with ingenious but materially simple table-top experiments taking advantage of their millimeter wavelength. The horn antennae, waveguides, and the semiconductor rectifiers he developed for detection

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prefigured the detailed exploration of microwaves and the knowing use of pn junction (silicon) rectifiers by half a century. One of his inventions, a biprism variable microwave attenuator, was incorporated in a 1.3 mm multi-beam receiver in the National Radio Astronomy Observatory (Arizona, USA) telescope in the mid nineties (Figure 1). In the early years of the 20th century, J. C. Bose began studying the electrical and mechanical response of plants to stress, by devising techniques of amplifying extremely minute movements and changes. Clearly it was far too early to make scientific sense of the striking results, and their often anthropomorphic description in a literal minded scientific age did not help. This scientific explorer was also a great teacher, emphasizing demonstration and experiment.

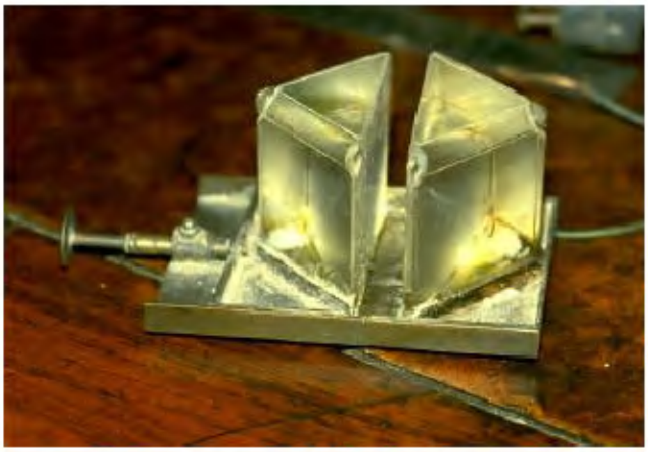

Figure 1*a*. One of Bose's original double-prism attenuators, with an adjustable air gap.

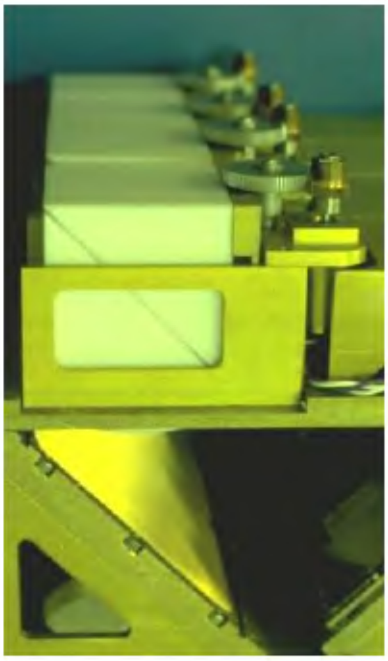

Figure 1*b*. Four of the 8 double-prism attenuators used to control local oscillator injection into the NRAO 1.3 mm 8-beam receiver in use at the 12 Meter Telescope at Kitt Peak.

Somewhat later came C. V. Raman (1888–1970), the greatest of Indian scientists. Precocious (his first scientific paper was published when he was about seventeen), indigenous and entirely self-taught, he was the natural scientist of the world of light and sound waves. The first half of his career (1907–1933) was spent in Calcutta and the remainder in Bangalore. He is best known for his discovery (Raman effect, discovered in 1928, Nobel Prize awarded in 1930) that photons interacting with matter can change their frequency, the shift being characteristic of its internal excitations. Prior to this, photons were known to be fully absorbed (e.g. photoelectric effect) or scattered elastically (ordinary or Rayleigh scattering of light, or Compton effect). The Raman effect, is a new phenomenon probing the internal states of molecules and of condensed matter. Some of the other major discoveries of Raman are the origin of the musical nature of the tabla and the mridangam, the diffraction of light from stationary wavefronts of ultrasound in liquids, light scattering from polymers and from short-lived shear fluctuations in fluids, and the soft mode associated with structural phase transitions in solids. Raman's style was imaginative and incisive, doing relatively simple but often ingenious experiments to probe phenomena. He was primarily a research scientist with a large number of research students over a long (~ 40 years) and productive scientific career; these students helped shape physics in India for a generation or more.

These two gifted experimental physicists, who flourished towards the end of the classical period in physics (Bose) and when quantum mechanics was being born (Raman) worked at a phase of the subject when it was possible with meagre facilities (generally the norm) to make major qualitative discoveries. That period, as we all known, is history and two major realities the world over are 'big' science, or 'small' science (laboratory scale) with sophisticated tools. We will discuss below the Indian physics experience in these two categories, but before that, mention some other physicists who made major contributions. Satyendranath Bose (1894–1974) was the first to realize the statistical mechanical consequences of identity in quantum physics (Bose–Einstein statistics) and applied it to light or photons, thus inventing quantum statistical mechanics. Meghnad Saha (1893–1956) showed that the origin of unusual stellar line spectra is the presence of different ionic species in stellar matter due to thermal removal of electrons, thus clarifying a great mystery in astrophysics and making it possible to know stellar temperatures. Saha was also active in public life, e.g. science and economic planning, calendar reform, a stint as nominated Member of Parliament, and founding and nurturing an Institute of Nuclear Physics in Calcutta, K. S.

Krishnan (1898–1961) collaborated in the discovery of the Raman effect, did very precise measurements of magnetic anisotropy in crystals and understood the results in terms of crystal fields, and also proposed a theory for the resistivity of liquid metals based on the scattering of free electrons by a dense highly correlated collection of atoms. The theoretical astrophysicist S. Chandrasekhar (1910–1995; Nobel Prize, 1983), started his epic career in India where he had begun to think at the age of twenty or so about the maximum mass a stable star can have, the Chandrasekhar limit.

These physicists worked mostly at universities, they being the only places for higher education and research in the pre-independence (1947) period except for two primarily research institutions, namely the Indian Association for the Cultivation of Science (Calcutta) and the Indian Institute of Science (Bangalore).

In the 1950s, the picture changed in several ways. India became independent in 1947. The charismatic Prime Minister Pandit Nehru believed strongly in nation building through centralized planning and government institutions, and in the essentiality of science both basic and applied for this. As a result, a large number of state-supported research and development laboratories were set up, for example, the cluster associated with the Council of Scientific and Industrial Research. This was also the period when 'big science' physics began to become prominent all over the world following the release of nuclear energy, and the atom bomb. The field found a visionary leader in Homi Bhabha (1909–1966), a fine theoretical physicist who was also close to Nehru. Bhabha conceived and helped set up a collection of institutions such as the Tata Institute of Fundamental Research (1945) and the Department of Atomic Energy (incorporated as Atomic Energy Commission in 1948) which itself had a wide spectrum of activities ranging from power reactors to metallurgy of nuclear fuel materials. He inculcated the spirit of self-sufficiency in instrumentation and technology development. He also built up people and groups, by choosing well, giving them the freedom and support needed, and generating and sustaining a spirit of great things to be done. In physics, a number of groups quickly attained international prominence (in the fifties and early sixties) in relatively new fields, e.g. cosmic ray research (or what would now be called nonaccelerator particle physics), neutron scattering and radio astronomy. For example, the occultation radio telescope at Ooty set up in 1970 due to the vision and leadership of Govind Swarup was a world class instrument, which provided important results relating the apparent size of galaxies with their luminosity.

I will now briefly summarize the present state of physics activity in India, then comment on it and against this background make some suggestions which may be of relevance for other third world countries as well. The attempted description will be sketchy, since the physics community is rather large, with perhaps 5000 or more Ph D physicists. At least nominally, most major areas of physics are pursued, so that there is a large and widespread knowledge and research base. This base is formed by the sustained efforts of a large number of dedicated practitioners working under difficult conditions, and a relatively small number of prominent figures or leaders, some of whom have made contributions of major significance to physics. A few individuals have successfully built and/or nurtured major institutions and facilities. Especially in government departments connected with atomic energy, space, defence, etc. a culture of self-reliance, of developing the tools needed, and of applied science at a high level of competence in diverse areas, has been developed.

In experimental physics research, a few areas stand out in terms of the investments made and facilities. These are overwhelmingly in the area of 'big' science. The Giant Metrewave Radio Telescope near Pune (with 34 parabolic dish antennas each of 45 m diameter, in a Y shape, with their signals synthesized electronically), now almost operational, has been conceived as a unique, world class facility in the 38–1420 MHz frequency range. There are many large optical telescopes including a remote operated one at Leh in the Ladakh Himalayas and a few others proposed. A number of medium energy machines have been functioning in the country, e.g. a heavy ion accelerator in the Nuclear Science Centre, Delhi, used as a common facility in Nuclear Physics and Materials Science for all Indian universities for about a decade. In 'small scale' physical science, the liquid crystals group at Raman Research Institute in Bangalore has been one of the pioneering centres in the exploration and study of this fascinatingly rich state of matter through the efforts of S. Chandrasekhar and colleagues. Their discovery of a new arrangement of liquid crystals, the discotic phase with stacking of disc-like molecules, is well known. Novel solid state systems with unusual and poorly understood electronic behaviour, e.g. cuprate superconductors, oxides exhibiting metal insulator transitions, fullerenes, carbon nanotubes and colossal magnetic resistance manganites, have been made, and several new phenomena discovered through the sustained efforts of C. N. R. Rao (Indian Institute of Science and Jawaharlal Nehru Centre, Bangalore) the solid state chemist and his group, and physicist colleagues such as A. K. Raychaudhuri and A. K. Sood (IISc, Bangalore). The Tata Institute group has been one of the leaders in exploring and describing phenomena in yet another large field, that of rare earth intermetallics, uncovering superconductivity in a new kind of magnetic solids (the rare earth borocarbides), and novel heavy fermion behaviour in many alloys.

Theoretical physics has a strong presence in India. There are about seven large groups (with more than five or six physicists; one, at the Tata Institute for Fundamental Research, has sixteen members) in the area of high energy physics, namely particle physics phenomenology and string theory, and a sizeable number spread in other institutions. In string theory, an area of great intellectual ferment, the Indian presence is quite prominent; for example Ashoke Sen (Harish-Chandra Research Institute, Allahabad) proposed the idea of strong-weak duality, and a number of physicists at TIFR contributed actively to the understanding of black hole entropy. In condensed matter there are two or so groups of five to six physicists, but several individuals and small groups scattered through the country. The Indian contribution in theoretical condensed matter physics ('hard' or quantum and 'soft' or classical) and statistical mechanics is very significant, often pioneering, in a variety of areas such as disordered electronic and classical systems, strongly correlated electrons and high temperature superconductivity, mesoscopic systems, self-organized criticality, exactly soluble one-dimensional quantum many body models, and complex systems. Theory of gravitation is a continuing tradition, starting with the early work of A. K. Raychaudhuri on black hole singularities, and of P. C. Vaidya on a black hole metric. Theoretical astrophysics and cosmology is an area of a large amount of high quality activity. In the area of quantum optics, the fruitful work of G. S. Agarwal is well known, as also the development of implications in optics of the Berry topological phase, now well recognized to have been discovered by S. Pancharatnam (in the mid and late fifties) in his description of the states of polarization of light.

There is, in physics, extremely poor support for laboratory scale ('small') science (e.g. condensed matter physics, materials science, modern optics and optoelectronics, nanoscience, soft matter) with unexamined and comparatively major support for 'big' science, e.g. observational astronomy and astrophysics (radio telescopes and optical telescopes). This has a historical origin, in that the perceived importance of physics-related discoveries in military power could be used in several Western countries to obtain public support for gigantic basic science projects exploring the small and the big. The Indian beginning in 'large scale' physics reflected that. The reality now is that two-thirds or more of physics in the last twenty or so years is 'small' scale. The reasons are many and well known – the richness and diversity of systems and phenomena, novel discoveries and concepts at different levels of organization, strong and increasing connection with many areas of science and engineering, wide and in many cases revolutionary applications. Unfortunately, this transformation is not reflected in our support of physical sciences. The fact is that big science the world over has become bigger, and except in astrophysics, less fruitful scientifically so that unless imaginatively conceived and executed, perhaps as an international facility and or with large, active quality participation from within the country (e.g. including the universities in a major way) Indian big science facilities are likely to be marginal contributors to science. Small science has became smaller (e.g. mesoscopic and nanoscopic systems), softer, and very sophisticated both in experimental techniques and intellectual content, and increasingly transdisciplinary. We are witnessing an outward bound movement of physics, and a coming together of different areas of science while the level of professionalism remains as high. This may be crucial for the future of physics.

Another characteristic is the clear phase separation between institutes and universities. Typically, the former tend to be small and well supported, generally outside the peer review system and by a large government agency such as the Department of Atomic Energy, or the Department of Science and Technology. The ratio of faculty to students is two or three to one. (Some centres such as the Bhabha Atomic Research Centre, do not have any students.) These are almost exclusively research institutes, and the physicists are generally quite capable. On the other hand, most higher education in science (or other fields) is in colleges (for undergraduates) or universities (postgraduates). These by contrast, deal with a large number of students and have, in general, been very poorly supported for a more than a generation with a few exceptions, and the research activity as well as professional quality under such circumstances is not as high, again with striking exceptions. The Indian Institute of Science and the Institutes of Technology are significantly different. The former is primarily a research institution with postgraduate teaching programmes, with faculty of very good quality, well supported via the peer review system, and with a faculty student ratio of one to three. The IITs are evolving into high quality institutions primarily for teaching select undergraduates, and postgraduates, with research activity not as prominent at least in physics, but considerable intrinsic strength in faculty. The relative research strength is crudely indicated by the number of Fellows of the Indian Academy of Sciences in Physics. Out of the total Physics Fellowship of 131, 86 are from the institutes, 23 from the universities and 22 from the IISc. The asymmetry is even more glaring in Astronomy and Astrophysics, where the ratio is 14 : 1. The present reality is likely to be worse since Fellows on the average tend to be over 50.

The third factor is social; there is a catastrophic decline in the number of students opting for physics (and chemistry and mathematics, not so much the life sciences) at the college (undergraduate) level, as it is a demanding course of studies with uncertain career prospects in comparison to a large number of information technology or electronics options which promise economic security and expanding opportunities. Also very few places offer attractive undergraduate science courses. This in turn obviously means a decline in the quality and number of physics background students in postgraduate (M Sc) courses and in research, the latter not being felt very acutely since the numbers involved are small.

Finally, the distance between industry and academic physics in India is specially large. A sizeable part of contemporary research physics is the basis of high technology, e.g. in semiconductor devices, optoelectronics, materials science. Related areas of technology are by and large conspicuously absent in India. Partial exceptions are those relevant to the mission of major agencies like Atomic Energy, Space, and Defence. This is not true of parts of chemistry and of life sciences to the same extent.

Thus, though the physics community in India is large, widespread (if nonuniformly) and strong, there are clear signs that major corrective actions need to be taken urgently not just for the vitality of physics in India, but for science and more importantly for the quality of our large society as it comes to terms with the economics, technology and science-driven world. In what follows, some suggestions are made.

The most fundamental change needed is one of mindset; in Indian physics, the prevailing perception has not effectively changed in half a century while the world of physics has been transformed. Of the three frontiers in physics, namely the big, the small and the complex, the first two have a natural grip on the imagination, being far removed from our scale. This, along with a view of the possible consequences of activity in this area and the mindset of successful advocates, have been effective in continuing support. While well thought out investment in this broad field makes obvious sense, it is crucial to realize that the third frontier of physics needs to be vigorously explored because of its intrinsic depth, richness and applicability. There is a naive belief that while this might be so, the amount of support needed is relatively small, and that it can be done with the existing scientific strength. The sophistication and variety of the tools required, and the experimental experience and intellectual training are such that this is not true, by a long margin. I estimate that on the average, about fifty crore rupees with the infusion of about a dozen or so high quality physicists nationwide, per year would be needed. The present support falls short by a factor of five to ten, and (partly as a consequence) in most major areas of laboratory scale experimental physics there are few practitioners of international quality. This has obvious consequences for possible applications, and for theoretical physics. In addition to support through government agencies, cooperative ventures involving more than one third world country, using the best strengths as they exist in one place or another, and seeded by the Third World Academy of Sciences, are a possibility that should be explored seriously. Another promising direction is private funding, which should find third world countries at a premium because of low operational costs and in many areas, availability of quality scientists.

For the long term stability and health of research and higher education, there is an urgent need to make universities the centres of these activities and to reshape, where possible, institutes into comprehensive university like places. It is a fact well confirmed all over the world, that undergraduate and postgraduate education and research are all best done together in a university, and that this is a very effective and stable arrangement since it bonds the university and society most strongly for their mutual benefit. In particular, quality undergraduate science education in a research university (not possible in India) has a strong effect on society through the contribution of persons with well trained, broadened minds and high level skills in a variety of areas. In addition, such an education will improve the quality and number of entering professionals and research scientists. In the longer run, our universities have to be vigorous and excellent centres, our society's biggest investment for a knowledge-based future. How this can be done with the present decision making and social forces is a difficult question; there are some attempts but nowhere near the right imaginative and financial efforts are being made. Meanwhile, two directions could be pursued so that undergraduate education of quality is widely accessible and possible.

One is to use the information now widely available over the internet (courses, lecture notes, problem sets, examinations, question and answer sites, etc.) to put together and disseminate widely (though printed/xeroxed copies, or electronically) consolidated world class learning material. If well done, this can be a great equalizer and quality enhancer, though not a full substitute for direct teaching. A few universities, colleges, institutes or individuals could act as nodes, adapting the material to our needs, making it easily available to lakhs of students and teachers, changing by these means the way science is taught and worked. Surprisingly, while there is a great deal of activity in this area in the West (e.g. the MIT has announced its intention to put all its courses on the web in a few years), there is no effort that I know of in the third world to create widespread quality education, sidestepping the problem of spotty teaching and absence/unaffordability of quality books and course material. Similarly, there have been several notably successful efforts in India at developing laboratory equipment which is versatile, contemporary and affordable. Unfortunately, these have remained relatively isolated while they need to spread throughout our educational system. All this presupposes that (undergraduate) science education of quality will be actively promoted and will be widely perceived as an attractive option by young people.

Another possibility is of several science institutions located in one geographical area joining together and starting, flexible undergraduate programmes. This should be done such that the research activities of these institutions are strengthened so that the new departure is welcome. It will provide an attractive, flexible and expansive choice to young students, and will help ensure long term stability to the concerned institutions. In India, with the right vision, planning and financial support, such new inter-institutional universities can be started in half a dozen places. I think that this should be possible in several other countries as well, where research centres are academically strong. Financial support for such imaginative ventures could be sought from private sources, notably the Indian diaspora and electronic age leaders.